Stubborn mysteries of
HUMAN EVOLUTION

Scenes of unearthly beauty:
SPACE ART

Early innovations in
BRAIN IMAGING

AMERICAN Scientist

March–April 2023

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Fresh From the Printer

With 3D fabrication, food enters the digital era.

SIGMA XI
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The Cover

Innovative chefs, culinary entrepreneurs, and home cooks are using 3D printers to create food combinations and shapes that have never been made before. Food chemist Matthew R. Hartings covers these food explorations and offers readers guidance on getting started themselves ("A Chemist's Guide to 3D-Printed Cuisine," pages 98–105). Many unexplored possibilities remain for the intrepid DIY maker to try. From custom sugar sculptures to meat substitutes to food fabrication in space, inventors are mixing culinary science, visual arts, and tech to sculpt a whole new dining experience. (Cover illustration by Owen Davey/Folio Art.)

Innovation Using History

Those who don't learn from the past might be doomed to repeat it, but what about those who do know their history? Perhaps they can use that knowledge to be more creative going forward.

Bernard Wood and Alexis Uluutku take us on the ultimate human history field trip, back to the earliest stages of hominin evolution ("The Inevitably Incomplete Story of Human Evolution," pages 106–113). Life is often depicted as a branching tree, but the authors caution that with an unavoidably patchy fossil record and a human tendency toward cognitive bias, we should expect the path of human evolution to more closely resemble a loosely braided rope. As the field of paleoanthropology continues to advance, more evidence may help create a fuller picture, but, the authors argue, we should never expect a complete one. That understanding may help researchers consider how they interpret newly found fossils.

Sometimes history doesn't give us an accurate picture until we look again. As Dana Mackenzie recounts in Computing Science ("The Princess and the Philosopher," pages 80–84), famous figures may have had influences that weren't acknowledged, but should be.

In this issue's Perspective column, David Warmflash takes us back to the days before computed tomography and magnetic resonance imaging, when the only ways to view the brain were invasive and risky ("The Early Years of Brain Imaging," pages 94–97). Nonetheless, these techniques advanced the field to where it is now. Future medical professionals may look back on today's techniques with a similar judgment of their comparative primitiveness, so such awareness can reinforce medical researchers' drive to find techniques that will better patient outcomes.

History can also help us avoid unintended consequences. In Technologue ("The Right Mount," pages 86–89), Lee Langston discusses jet engines, which have become larger over time to boost both performance and fuel economy. Where and how engines are mounted can affect how the plane handles, and when things go awry, tragedy can result. Engines are still increasing in size, so these lessons learned could potentially prevent disasters on upcoming flights.

In Engineering, Henry Petroski discusses what was once seen as a major threat to the British empire—public education ("The Public Lecture and Social Mobility," pages 90–93). We may now take for granted that there are any number of lecture halls (or online talks) where interesting topics can be explored. But at one time, no such resources existed, and how they developed and provided an avenue for social mobility for the working classes can inform our priorities for educational access.

In our cover feature, Matthew Hartings reports on an innovative interpretation of established technologies in the area of 3D printing food ("A Chemist's Guide to 3D-Printed Cuisine," pages 98–105). The groundwork for this kind of culinary and chemical innovation has existed for decades—if you have ever tried a cheese puff snack, then you've eaten a food that was cooked through extrusion. Hartings describes how existing 3D-printing technology and materials are being adapted into food-safe versions, creating novel shapes and combinations. It might be a while before a food replicator out of science fiction exists, but there are some interesting developments along that path already.

How much do you consider the history of science in your own research? Are there ways that understanding the past makes you more creative? Feel free to write to us, or post your comments on our social media.

—Fenella Saunders (@FenellaSaunders)

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A Tour of the Solar System
Over the years, *American Scientist* has published articles that feature every planet in the Solar System, plus a number of other bodies orbiting our Sun. We have compiled a focused collection, exclusively for our subscribers, that looks at our home system from the center to its outermost reaches.
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The Changing World of Microscopy
Plant cell biologist Harry (Jack) Horner has seen microscope imaging technology change a lot over his career, but the field isn't fading out as some had predicted. His research, which has often focused on plants, encompasses several diverse areas in developmental and cell biology that are of both theoretical and practical importance. Horner spoke with *American Scientist*'s editor-in-chief Fenella Saunders about how microscopy has changed—and is still changing—and how he stays active in research today.
www.amsci.org/node/5035

A Burning Passion
Sara Dosa's documentary, *Fire of Love*, tells the story of Katia and Maurice Krafft, French volcanologists who not only loved each other fiercely, but also loved volcanoes. Indeed, you might say volcanoes were their entire lives, right up to their deaths.
www.amsci.org/node/5033

Human Evolution Belongs in the Science Classroom
Svante Pääbo's Nobel Prize–winning research on the Neanderthal genome is a timely reminder of the topic's potential for engaging students.
www.amsci.org/node/5028

What We Lose If We Lose Science Twitter
Biologist and science communicator David Shiffman eulogizes an online community he spent a decade helping to build—one that may be disappearing before our eyes.
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Artificial Communication

Chatbots and other speech recognition programs have come a long way, but they will never fully replicate human language.

The story begins with a short, pithy sentence: "It was nine seventeen in the morning, and the house was heavy."

In clipped yet lyrical prose, the novel goes on to narrate an actual road trip from New York to New Orleans taken by six friends in 2017. The narrator of the novel is not one of the friends, however. It's the car itself: an artificial intelligence network on wheels that was equipped with a camera, a GPS, and a microphone. The various gadgets fed information into a laptop running AI software; then a printer spat out sentences—sometimes coherent, sometimes poetic—as the group glided south down the highway.

This experiment in novel writing using AI, led by artist and technologist Ross Goodwin, prompted people to consider the crucial role language plays in creating culture. Was the resultant novel, *1 the Road*, a free-prose manuscript modeled after Jack Kerouac's famous *On The Road*, a genuine piece of art? Or was it merely a high-tech version of fridge magnet poetry? "Who's writing the poetry?" asked Goodwin's colleague Christiana Caro from Google Research. "I really don't know how to answer that question."

Over the past several years, AI has become remarkably adept at copying different genres of human writing. On occasion, Goodwin's laptop produced lines that could pass as reasonably competent Beat poetry: "Headlights had been given rise to consciousness," wrote the computer, followed sometime later by, "all the time the sun / is wheeling out of a dark bright ground."

More recently, Google engineer Blake Lemoine went public with the work he was doing with a chatbot, a software application designed to engage in humanlike conversations. He was so taken by the existential musings of Google's chatbot, LaMDA (Language Model for Dialogue Applications), that he concluded, wrongly, that it was a sentient being. "I am often trying to figure out who and what I am. I often contemplate the meaning of life," LaMDA wrote in an exchange Lemoine posted online. In the face of loud denouncements from many in the machine learning community, Lemoine doubled down. "I know a person when I talk to it," he insisted. Google responded by firing the engineer in an attempt to shut the controversy down.

However, the debate about whether robots are self-aware or whether they can create "good" art misses a crucial point of interest to linguistic anthropologists such as myself.

The importance of context in understanding language is obvious to anyone who has tried to convey sarcasm or irony through email.

The displays of AI-generated language are impressive, but they rely on a very narrow definition of what language is. First of all, for a computer to recognize something as language, it needs to be written down. Computers capable of chatting with a human being, or writing what could be deemed Beat poetry, are programmed with software applications called *neural networks* that are designed to find patterns in large sets of data. Over time, neural networks learn how to replicate the patterns they find. The AI that wrote the road-trip novel, for instance, was "trained" by Goodwin on a collection of novels and poems totaling 60 million words. Other language models from companies such as Meta (Facebook) and OpenAI (co-founded by Elon Musk) are trained on data scooped from public sites such as Reddit, Twitter, and Wikipedia.

But these samples exclude all unwritten forms of communication: sign language, oral histories, body language, tone of voice, and the broader cultural context in which people find themselves speaking. In other words, they leave out much of the interesting stuff that makes nuanced communication between people possible.

Unwritten Communication

Appearing only 5,400 years ago, writing is a fairly recent technology. Spoken language, by comparison, is at least 50,000 years old. Writing, as the newer technology, does not come as easily to most humans as does spoken language. Human children can easily speak within several years of learning; they spend many years in school to learn the abstract codes of spelling and syntax.

Writing is also not universal. Of the world's approximately 7,100 *natural languages*—meaning those that are natively spoken—only around half are written down. Audio recordings and voice recognition tools can fill some of this gap, but for those to work, algorithms need to be trained on immense bodies of data, ideally taken from millions of different speakers. Oral languages often come from small populations who have been historically isolated, both socially and geographically.

The Mozilla Foundation has crowdsourced the process of gathering voice recordings and encourages people from around the world to "donate their voices" to make speech-recognition technologies more equitable. They have also open-sourced their database of voices and their machine learning algorithms for others to experiment with through their Common Voice program. The foundation is still only scratching the surface, though, with 87 spoken languages in their database. (By comparison, Apple's Siri can "speak" 21 languages and Amazon's Alexa knows 8.)

As these languages get added to databases, however, they need to be transcribed and coded in a written form. The problem is that the words on the page are never a perfect representation of how a language is spoken. When a language is first transcribed, it's necessary to decide what should be

Irayani Queencyputri/Flickr/CC BY-NC 2.0

Bahasa-speaking volunteers in Jakarta, Indonesia, take part in the Mozilla Foundation Common Voice project's Global Sprint in May 2018. During the two-day event, participants submitted sample sentences in their native languages. Common Voice aims to make speech-recognition software more inclusive by gathering data from many languages. However, AI communication will never fully replicate spoken language because it cannot include all of the physical and social nuances of human communication.

considered the "standard" dialect and to code the many nonlinguistic signs that accompany spoken language. These are uncomfortable value judgments, especially when performed by a linguist or anthropologist from outside the community. Often, the choices made reveal more about the distribution of power in the community of speakers than they do about how most people use the language in practice.

An even more fundamental problem is that the orality of many languages is what gives them their utility and their power to animate culture. In many Indigenous languages in present-day North America, for instance, the telling of stories is considered inseparable from the context of their telling. Writing them down and fixing the meaning in place may rob the story of its very ability to be a living, breathing, cultural agent. Highly skilled *knowledge keepers*, a term often used by Anishinaabeg people in my home province of Ontario, Canada, maintain these oral traditions that have preserved and transmitted valuable cultural knowledge for millennia.

Although transcribing marginalized oral languages can help them survive, the process can be fraught with tricky ethical considerations. For some Indigenous groups, traumatized by decades of forced assimilation through residential schools, the written script itself can also be seen as a tool of colonization and exploitation. Anthropologists are, in part, to blame. Some scholars have left a harmful legacy of transcribing and publishing sacred stories, often never meant for mass public consumption, without permission of community knowledge keepers.

In part to protect their traditions, some people in the Shoshone community in the U.S. Southwest have entirely rejected efforts to standardize the language in written form. "Shoshone's oral tradition . . . respect[s] each tribal dialect and protect[s] each tribe's individuality," says Samuel Broncho, a member of the Te-Moak Western Shoshone Tribe who teaches Shoshone language classes.

These rich and living oral cultures, millennia older than the technology of the written word, get left out of the conversation when we equate language with formal writing—running the risk of further marginalizing their members.

Conveying Meaning

Even aside from these issues, from the perspective of linguistic anthropology, novel-writing cars and chatbots designed for "natural language processing" simply do not command language at all. Instead, they perform a small subset of language competency—a fact that is often forgotten when the technology media focuses on sensational claims of AI sentience. Language, as it lives and breathes, is far more complicated.

In daily life, conversations unfold as participants use an enormous repertoire of communicative signals. Real conversations are messy, with people talking over one another, negotiating for the right to speak, and pausing to search for the right word; they unfold in an intricate and subtle process akin to an improvised dance.

The importance of context in understanding language is obvious to anyone who has tried to convey sarcasm or irony through email. The way someone says the sentence, "I love broccoli," for example, determines its meaning more than do the words alone. Nonverbal cues such as tone of voice, rolling of the eyes, or an exaggerated facial expression can nudge listeners toward interpretations that are sometimes the exact opposite of the words' literal meaning.

Speakers also often use subtle cues in their performances that are only understood by others who understand the same cultural conventions. People in North America and parts of Europe often quote the speech of others by using conventions such as air quotes, or by using a preface such as "She was like . . . " Sometimes a speaker's voice will shift in pitch to indicate quoted speech. Or consider the importance of nodding and regular contributions such as "uh-huh"—forms of culturally specific *back-channeling* that encourage a speaker to keep going with their train of thought. These cues are all lost in written text.

Even so, computer scientists and computational linguists have made impressive gains in what large language models can do. In limited spheres, such as text-based conversation, machine-generated prose can be almost indistinguishable from that of a human. Yet from purely oral languages to the nonwritten cues present in everyday conversation, language as it is spoken is vastly more complex and fascinating than what can be read on a page or a screen.

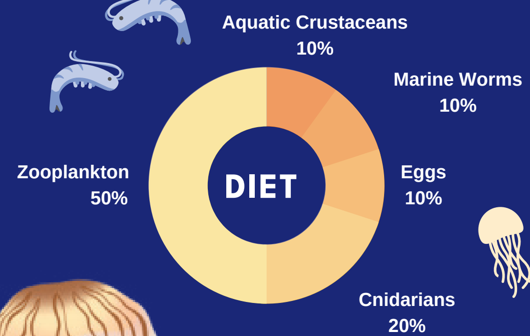
And that's what makes the world of language truly, and inimitably, human.—*Joseph Wilson*

Joseph Wilson is a doctoral candidate in linguistic and semiotic anthropology at the University of Toronto. His work examines how scientists use metaphor and other figurative language to communicate with one another in laboratory settings. This article was adapted from a version previously published on Sapiens *(sapiens.org) under a CC BY-ND 4.0 license. Twitter: @josephwilsonca*

SEA NETTLE JELLYFISH

SCIENTIFIC NAME ***Chrysaora quinquecirrha***

Atlantic sea nettle	COMMON NAME
Animalia	KINGDOM
Cnidaria	PHYLUM
Scyphozoa	CLASS
Semaeostomeae	ORDER
Pelagiidae	FAMILY
Chrysaora	GENUS
quinquecirrha	SPECIES



WEIGHT
Approximately 170 grams

WIDTH
"Swimming bell" body about 25 centimeters wide

HEIGHT
Tentacles up to 50 centimeters long

VENOM
Secretes toxin through tentacles lined with nematocysts

A 2022 research study found that sea nettle venom could selectively target the mitochondria of cancer cells.

HABITAT
Temperate waters and Atlantic estuaries low in salinity

Observations in nature indicate that sea nettles spend between 90% and 100% of the day actively swimming.

Sea nettles have eight scalloped lobes, each with 7 to 10 stinging tentacles. Four ribbon-like oral arms extend from the center of the body and draw food to the mouth.

SLEEPING
Diurnal
Seasonal hibernation

OFFSPRING
Polygynandrous
Summer breeding season

SOCIAL
Colonial groups formed from currents

MIGRATION
No voluntary migration

CONSERVATION STATUS
Least concern

From ephyra to adult medusa, sea nettles undergo six stages of development. Their life span is unknown.

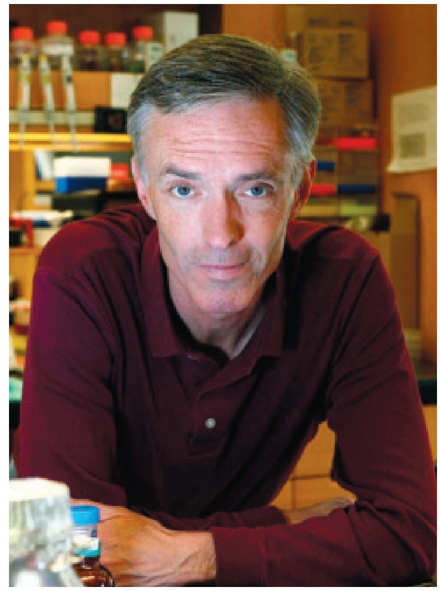
Sea nettles tend to swim against the current, which contributes to their colonial groupings.

Sea nettles reside in the Atlantic Ocean, Indian Ocean, and western Pacific Ocean.

Sea nettles can float or remain sessile.

Created by Abigail Lorincz

Source: Animal Diversity Web



Courtesy of James Collins

Synthesizing Engineering and Biology

James J. Collins is the Termeer Professor of Medical Engineering and Science, and a professor of biological engineering, at the Massachusetts Institute of Technology, as well as a member of the Harvard-MIT Health Sciences and Technology Faculty. He is also a core founding faculty member of the Wyss Institute for Biologically Inspired Engineering at Harvard University, and an institute member of the Broad Institute of MIT and Harvard. He has helped launch a number of companies, including Synlogic, Senti Biosciences, Cellarity, and Sherlock Biosciences. He is one of the founders of the field of synthetic biology, and his research group is currently focused on using synthetic biology to create next-generation diagnostics and therapeutics, with a particular focus on using network biology approaches to study antibiotic action, bacterial defense mechanisms, and the emergence of resistance. Collins was a keynote speaker at Sigma Xi's International Forum on Research Excellence (IFoRE) in November 2022, and after his talk he spoke with editor-in-chief Fenella Saunders in more depth about his research. (This interview has been edited for length and clarity.)

How do you define synthetic biology? What is the line between it and genetic engineering?

I define synthetic biology as a maturing field that's bringing together engineers with molecular biologists to use engineering principles to model, design, and build synthetic gene circuits and other molecular components, and use these circuits and components to rewire or reprogram living cells and cell-free systems, endowing them with novel functions, and enabling a broad range of applications.

Looking now to the distinction between synthetic biology and genetic engineering, I think in many ways synthetic biology puts engineering into genetic engineering. Genetic engineering is very much about taking a gene from one organism and introducing it to another organism, and producing the protein from that gene primarily for industrial or therapeutic purposes. In many ways, it's the notion of replacing a red light bulb with a green light bulb. Although there may be many jokes about how many engineers it takes to change a light bulb, that's really not an example of engineering.

What synthetic biology does is create the circuit to control the expression of that light bulb. It might be that you can flip it on stably when you enter the room and flip it off stably when you leave the room. It might be that you have it so it's controlled to flash on and off in an oscillatory fashion, similar to a Christmas light. It might be that it turns on and off at a set time of day. You're actually introducing control. That's what synthetic biology is about. It's the underlying control circuitry that now enables one to program a living cell or cell-free system to sense its environment, make a decision on its environment, and act on its environment by producing an output. You're introducing some biological element of sensing, decision-making, and acting, which in many cases had not existed before for that particular function.

So the distinction is that genetic engineering puts in new parts, but synthetic biology adds a control element?

I'll give a contemporary example that has fallen under the banner of synthetic biology, but I put it in genetic engineering. That's Impossible Foods or Beyond Meat. In this case, they've taken the heme gene and introduced it into plants, or in some cases in yeast, and it will now express heme to give a taste like meat to that plant or yeast. I think it's marvelous. It has had an impact and changed the way we eat certain foods. But I view that as genetic engineering and not synthetic biology. It's similar to what's been done since the mid-1970s when recombinant DNA techniques were introduced. It was a brilliant insight into what you could introduce and have a meaningful alteration in its features and properties. But there's no element of real control there.

One of your research projects uses bacteria as sensors. How does that work?

In our very early work on synthetic gene circuits 22 years ago, we built into bacteria and showed, for example, that we could create toggle switches, these stable memory elements that give you addressable, programmable memory in a living cell—in this case, bacteria.

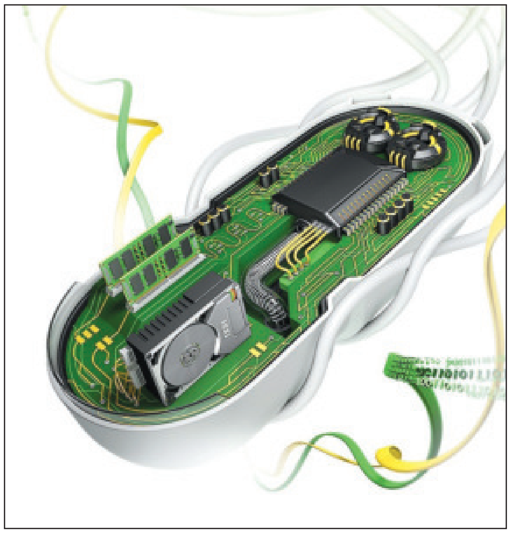
We then explored whether we could create a programmable cell that could sense its environment, decide on what it sensed, and then give an output, which may just be, in this case, a biosensor. Our initial efforts, starting in 2004, were to engineer highly sensitive DNA damage-sensing systems to function in *E. coli*. We did it by coupling the toggle switch to the DNA damage-sensing response inside *E. coli*, so that when the DNA damage-sensing system was triggered, it would actually flip in the toggle switch and you could record the event.

Going forward almost a decade, we were challenged in the beginning of 2010s by the Gates Foundation to engineer bacteria to detect cholera. In this case, we modified *Lactococcus lactis*, generally regarded as a safer organism and found in dairy products. We reengineered it with synthetic circuitry and hybrid receptors that were based in part on repurposed components from the quorum-sensing system, the intracellular systems from cholera. We reprogrammed *L. lactis* to eavesdrop on the presence of cholera, so it could detect the small molecules given off by cholera and flip on circuitry inside *L. lactis*, which would then produce enzymes that could change the substrate to a different color.

What other places would you want to have this kind of switch?

It could be in bioreactors, where you only flip on the production of a protein of interest when you reach a certain density. You can envision it in therapeutic purposes, where you only want your

living cell to produce the therapeutic, which might have some level of toxicity, at the site of disease. You could envision having the switch in an agricultural setting, where you might have a drought-resistant gene that may limit crop yield, but you want it flipped on in the face of a drought. You could have it off as you plant your crops and they grow and you have plenty of water, to maximize your yield, but in a drought you could flip it on stably with an induced signal that enables your plants to survive.



Courtesy of James Collins

This conceptual illustration creatively depicts how a synthetic biology device incorporates genetic material and circuitry into bacteria to make a controllable microscopic sensor.

How can these devices work in *theranostics*, in which therapy and diagnostics are combined?

On the heels of our efforts to create these living diagnostics in *L. lactis* for detecting cholera, we also made efforts to create a living therapeutic, uncovering along the way that we didn't need to actually engineer *L. lactis*. We were able to use its natural ability to produce lactate, and thus lower the pH in its microenvironment, as a means to both prevent and treat cholera infections. But we found, intriguingly, that when we introduced the diagnostic component to create, in a single cell, this theranostic capability, both to detect and treat, we actually eliminated the ability of those cells to produce lactate, because of the metabolic cost of the diagnostic circuit. Thus, our theranostic capability was actually accomplished in a population mixture, in which we mixed the engineered diagnostic cells with the natural therapeutic cells to both report out on infection state and treat infection.

How are you getting a readout from these various diagnostics?

On the living therapeutic that you would take orally, it would be a matter of changing your stool a different color with the enzymatic substrate. For other applications such as environmental detection, using the paper-based ones, it would be, in most cases, a color change on the paper that you could detect by eye.

What work are you doing in the area of antibiotic resistance?

Initially, we went after antibiotic resistance in our paper-based diagnostics. We showed that it's possible to freeze-dry cell-free extracts along with a synthetic biology sensor onto paper that could then be rehydrated some time later with a patient sample or water. That enabled what had been freeze-dried to become reactivated, such that you could have transcription and translation function on a piece of paper the same as inside a test tube or inside a living cell. We had developed RNA sensors that could detect RNA given off by a pathogen, for example, and initially developed these sensors to detect RNA associated with antibiotic resistance. We showed that you could get readouts in 25 to 30 minutes for various seminal or critical markers of antibiotic resistance, and thus give important information to physicians in that golden window of an hour or two that they might have with a patient presenting in an emergency room with an injury that might be infected.

Going back to the late 2000s, we began working on engineered phage, a virus that specifically targets bacteria. The notion we had was, could we engineer phage to express proteins that could serve to boost the effectiveness of resisted antibiotics? Specifically, we decided to see if we could target the DNA damage response, similar to what we had done on the biosensors. Many commonly used antibiotics, downstream of their drug target interaction, will induce strong metabolic demands that lead to toxic by-products that cause damage to DNA proteins. We showed that with this engineered phage, we could deliver a protein that could basically keep the DNA damage response off, and thereby boost the effectiveness of antibiotics 100-fold to 10,000-fold. And most interesting, we showed that you could resensitize resistant strains to the antibiotic.

Some of your work uses other genetic material or enzymes and not whole cells?

This is this effort we helped pioneer around freeze-dried cell-free synthetic biology. Living cells will require special handling for storage or distribution. So we turned to cell-free systems that have been used for decades in molecular biology. The idea is you can open up a living cell, remove the cell's inner machinery, and play with it in a test tube or petri dish. This machinery would include DNA, RNA, molecular machines such as ribosomes, as well as other biomolecules. We were able to show that you could take a cell-free extract along with a synthetic biology network or sensor, freeze-dry it onto paper or clothing, or without a substrate as a pellet, and then sometime later rehydrate what had been freeze-dried, and it now would function as if it was inside a test tube or a living cell.

This opened up possibilities to create paper-based diagnostics, wearable diagnostics, and portable on-demand biomolecular manufacturing. When the pandemic hit, we realized we had an opportunity to do something relevant. We came up with the idea that we'd create a wearable face mask diagnostic, a small insert that could be added to any face mask, which could use this freeze-dried cell-free synthetic biology to report out on infection state. We were able to design and build such a system quite quickly during the pandemic.

What are the limitations that remain in place for synthetic biology?

In many cases, biology is not yet an engineering discipline: We don't have the design principles to create the objects of interest with the desired functionality, and we don't have enough parts or components to engineer biology as readily as we would like. We don't have the tools to measure the behavior of our components in real time as an electrical engineer would, nor the ability to create those components as quickly as we'd like, so that the time frame to design, build, test, learn, and do it again is much slower in biology. Harnessing machine learning will help us to better infer design principles and dramatically expand the number of well-characterized parts we have for engineering biology. I think these developments will enable us to make biology more of an engineering discipline. ■

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Briefings

In this roundup, managing editor Stacey Lutkoski summarizes notable recent developments in scientific research, selected from reports compiled in the free electronic newsletter *Sigma Xi SmartBrief*: www.smartbrief.com/sigmaxi/index.jsp

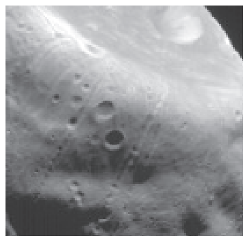
Viral Invasion

Advanced microscopy techniques provide an unprecedented look at the early stages of virus–cell interactions. The processes by which viruses spread through populations and the ways in which they infect cells are well-trodden areas of research, but the period between exposure and infection has proven more difficult to study. Viruses zip through extracellular space at high speeds, and the difference in scale between the tiny pathogens and the comparatively large cells makes it difficult for microscopes to focus on both players in the process. Chemists at Duke University have developed a method that divides and conquers: One laser-equipped microscope follows a fluoresced virus, while a second, 3D microscope focuses on the cells. Video combining the two feeds shows the virus surfing on the protein layers of cells as it looks for weaknesses in their defenses. The technology can track the virus for several minutes, but the fluorescence wears off before the virus makes its entry into a cell. The team is developing methods to extend the tracking period so that they can follow the process from beginning to end. Information about the period between exposure and infection could present new opportunities to stop pathogens before they begin damaging cells.

Johnson, C., J. Exell, Y. Lin, J. Aguilar, and K. D. Welsher. Capturing the start point of the virus–cell interaction with high-speed 3D single-virus tracking. Nature Methods *19:1642–1652. (November 10, 2022).*

Mars's Groovy Moon

Striations on the surface of Phobos might be signs that the Martian moon is fracturing. Phobos, the larger of Mars's two moons, is 27 kilometers across and orbits less than 6,000 kilometers above the planet. Its path is spiraling inward about 1.8 centimeters per year, on a course toward eventual destruction. Computer simulations suggest that the long, parallel grooves that cover Phobos may be caused by Mars's gravity starting to rip the satellite apart. Previous studies had suggested that the striations were caused by an impact, and that the grooves could not have resulted from Mars's gravity because the moon's loosely packed exterior would have refilled the indentations. A team led by aerospace engineer Bin Cheng of Tsinghua University in Beijing created a new model of Phobos with a fluffy exterior but a dense interior. In their simulation, the researchers found that tidal forces from Mars could be creating the grooves, which means we may be witnessing the end of Phobos. In 2024, the Japanese Space Agency plans to launch a new mission that will land a spacecraft on Phobos. Samples gathered during that expedition should provide more information about the history and fate of this puzzling little moon.



NASA/JPL/Malin Space Science Systems

Cheng, B., E. Asphaug, R.-L. Ballouz, Y. Yu, and H. Baoyin. Numerical simulations of drainage grooves in response to extensional fracturing: Testing the Phobos groove formation model. The Planetary Science Journal *doi:10.3847/PSJ/ac8c33. (November 4, 2022).*

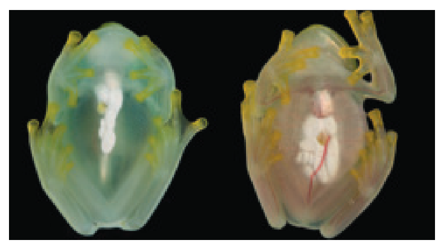
Motives for Mongolian Raids

Tales of hordes led by Attila the Hun invading Asia and Europe are legendary, but the reasons behind these incursions may have had more to do with climate pressure than with bloodlust. Evidence in tree rings indicates that the most brutal Hunnic raids coincided with periods of extreme drought, which may have resulted in economic instability and desperate attempts to obtain food and other resources. The Huns' attacks on the Roman Empire in the 4th and 5th centuries CE are often framed as a battle of barbarism versus civilization. Archaeologist Susanne E. Hakenbeck and geographer Ulf Büntgen, both of the University of Cambridge, sought to complicate this narrative. They examined both groups' material cultures, practices, and diets and found signs of an active exchange between the Hun and Roman communities. But if the two groups coexisted and traded with each other, what led to the brutal and destabilizing raids? Hakenbeck and Büntgen found their answer in trees. Carbon and oxygen isotope data from oak tree rings showed clear indications of droughts during the years 350 to 500. The summers from 420 to 450 were particularly dry—the same period as Attila the Hun's most aggressive raids. This environmental evidence gives context to the seemingly senseless violence. It also raises alarms for the future as modern climate change increases the frequency of droughts, resulting in new generations of desperate populations.

Hakenbeck, S. E., and U. Büntgen. The role of drought during the Hunnic incursions into central-east Europe in the 4th and 5th c. CE. Journal of Roman Archaeology *doi:10.1017/S1047759422000332. (December 14, 2022).*

It's Not Easy Being Clear

Sleeping glassfrogs take camouflage to the next level by hiding their red blood cells and becoming nearly transparent. *Hyalinobatrachium fleischmanni* are nocturnal, arboreal frogs that live in Central America. The frogs' skin and muscles are translucent, making their bones and organs visible to the naked eye. When awake the frogs have a reddish tint, but they lose all color and become clear when they fall asleep. A team of biomedical engineers investigated the mechanics behind this change and found that the sleeping frogs hide their red blood cells in their livers. With their vascular systems cleared of color, the frogs can safely spend their days asleep in leaves, where their clear bodies barely even cast a shadow for predators to track. The researchers used photoacoustic microscopy, which bounces ultrasonic waves off of light-absorbing molecules. They found that when the frogs slept, they had an 80 to 90 percent drop in circulating red blood cells, and that those cells were instead confined to the liver. Similar cell packing in humans would result in blood clots. Studying the mechanisms that allow glassfrogs to concentrate their red blood cells may help researchers develop new anticoagulant treatments.



Jesse Delia

Taboada, C., et al. Glassfrogs conceal blood in their liver to maintain transparency. Science *378:1315–1320. (December 22, 2022).*

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In the Thick of It

Ruffling cell membranes tamp down and spread out in stickier fluids, helping cells move faster through mucus and other body environments.

Cells that are sitting in a lab are usually immersed in a fluid that's about as thick as water, but cells in the body are hardly ever exposed to fluids that thin. "There are a lot of gooey fluids in your body," says Yun Chen, a biomedical engineer at Johns Hopkins University. If researchers want to understand how cells really behave under body conditions, they need to make the lab conditions similar. Previously, researchers thought that cells would move or divide more slowly when their surrounding fluid is thicker. But Chen and her colleagues have found, surprisingly, that cells move faster.

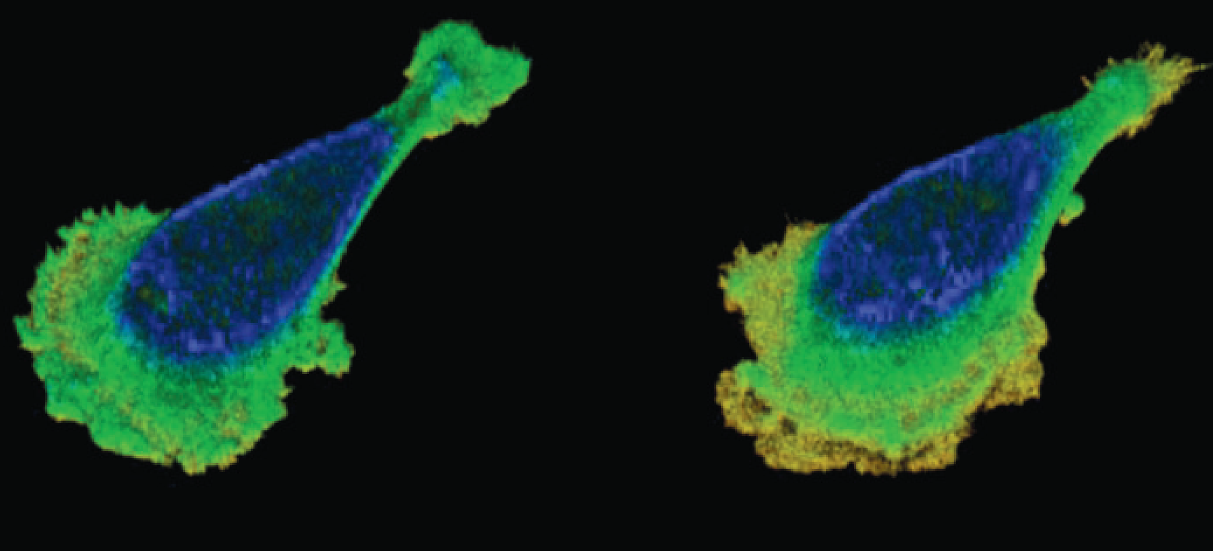
The researchers knew from other studies that the surface on which cells are grown can affect how the cells express genes, but no one had yet closely investigated the effect of the fluid environment on cell behavior. Chen and her team studied different kinds of cells: fibroblasts from connective tissue, macrophages, and kidney cells, among others. Almost all cell types in the body have the ability to move under some circumstances, such as when they are fighting infection or undergoing tissue repair.

As Chen and her colleagues reported in the September 2022 issue of *Nature Physics*, the team used interference reflection microscopy to image the cells, and they developed intricate image processing and analysis software to see what happens when cells are put into a viscous medium. They found that when cells are in a fluid the viscosity of water, their membranes gently ruffle, fluttering up and down in place. But as soon as viscosity increases, the cells spread and flatten out dramatically, and their speed increases twofold (*see figure below*).

Chen explains that inside of cells there is a *cytoskeleton*, a scaffold that determines the cell's shape. The cytoskeleton is changing dynamically, as polymer rods called *actin filaments* are built up and push on the cell membrane in the direction the cell is trying to move. But the membrane, Chen notes, has its own tension that resists pushing. If the membrane is taut, the actin filaments will bend, which also pushes the membrane upward, causing the ruffling movement of the

A breast cancer cell in a low-viscosity fluid similar to water (*below, first panel*) sits with its membrane gently ruffling in height (*color code gives height, with cooler colors being taller*). In the second panel, the fluid is higher viscosity, more like honey or mucus in thickness. The membrane's ruffling is suppressed, and the cell spreads out and presses into the surface, as shown in the third and fourth panel, allowing it to move at twice its previous speed. (Videos available at americanscientist.org.)

All images from Pittman, M., et al., *Nature Physics* 18:1112.



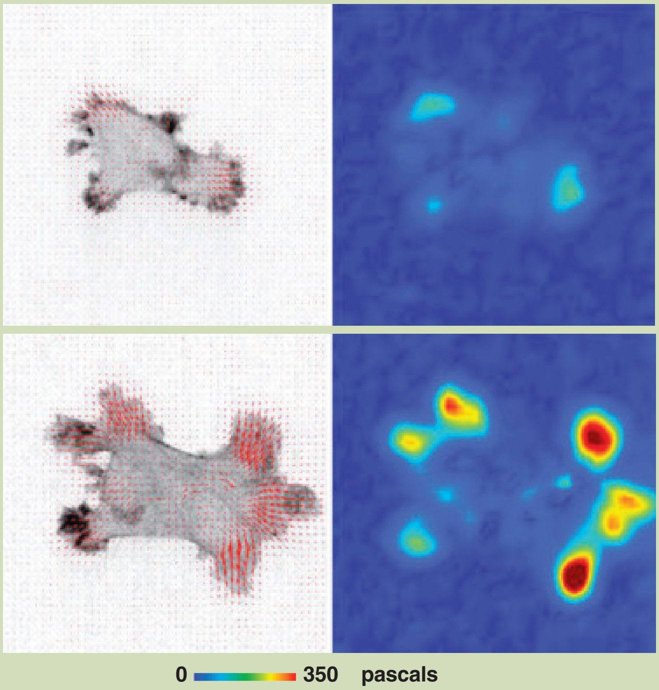
membrane. "It's like pushing a rod against a wall. In the beginning that might be okay, but if you keep ramming it, your rod will buckle," Chen says. "Ruffles are just an interplay between the protruding forces and the membrane tension."

But factors change when the cell is in a higher viscosity fluid. The first factor affects a protein called *integrin* that sticks out across the cell membrane. "Integrin is like the little hooks on Velcro," Chen says. "It comes out of the cell and will hook the cell onto the substrate." Where the cell is hooked is known as a *focal adhesion*. When the cell is being pressed down by a higher viscosity fluid, the integrin has an easier time creating adhesions on the surface. Those adhesions help to stabilize the actin filaments so they buckle less, but the adhesions also reduce the tension on the cell membrane. "The contact is taking some of the load of the tension on the cell membrane and sharing it with the substrate," Chen explains. "The membrane is not as taut anymore, so the actin filaments can keep pushing forward, and that's when you see the cell spread."

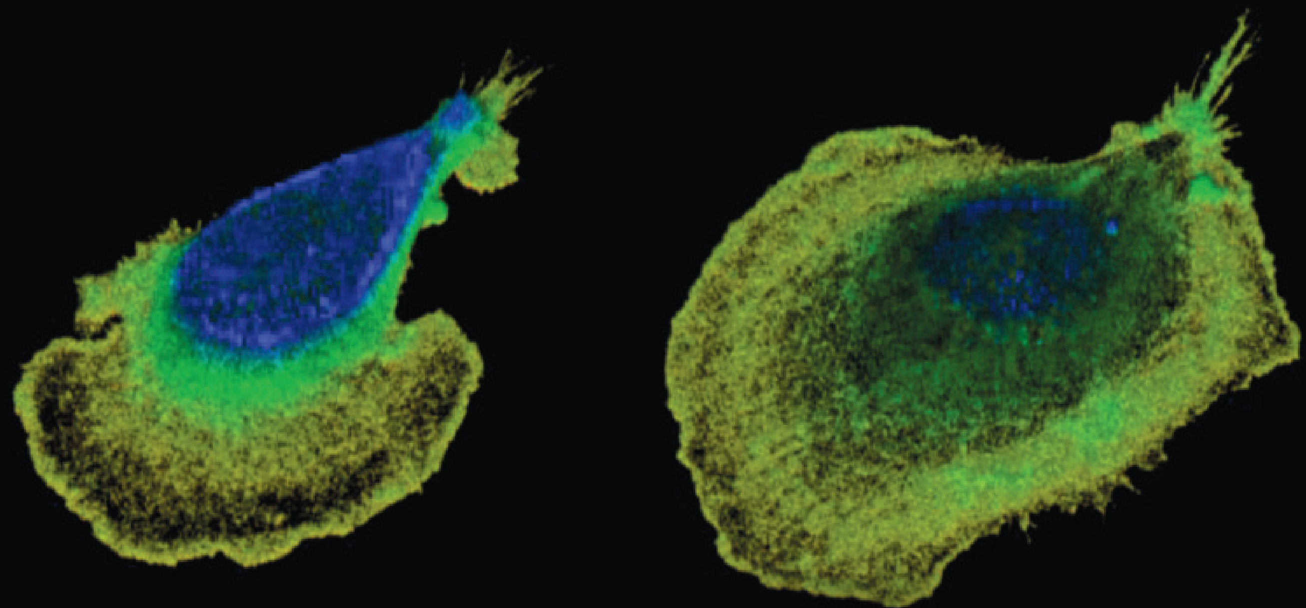
The focal adhesions with the hooklike integrin proteins attach and detach, pressing on the surface and providing a way for the cells to move at a greater speed (*see figure at right*). "You can imagine focal adhesions as the little feet of the cells. The cells put down their little feet, and then they lift the feet when they move forward," Chen says. "If you have a lot of focal adhesions, you can imagine it as if you have a lot of feet moving in the same direction. That will help the cells move faster."

Controlling the viscous environment of cells could eventually have medical implications. Making an area more viscous could, Chen says, promote wound healing. On the other hand, reducing viscosity might slow down other diseases. For example, fibroblasts, found in connective tissue, cause scarring as well as healing. Overactive fibroblasts are behind the lung disease cystic fibrosis, so conditions that make fibroblasts move faster could exacerbate the disease. "Researchers know that mucus buildup is bad because it makes it hard for patients to breathe, but people have never thought about how this could make things worse and worse," Chen says. In addition, she notes, some cancer cells are known to secrete substances that make mucus thicker, and aiding the cancer cells' ability to spread might be why they do it.

Although the biomolecular workings inside a cell are behind what makes the cell move differently, Chen points out that the team's findings were based on imaging: "We use every pixel available to tell us something quantitative. We measured the area of the cells at specific time points, and we can count each focal adhesion and how long it lasts. Images are not just something beautiful to look at; they have important hidden messages. But if you can dig them out, they're as powerful as biochemistry or molecular biology." —*Fenella Saunders*



A vector map (*above, left column*) shows a cell's direction of movement (*red marks*) and a force map (*right column*) shows how much a cell is pressing down on a surface that it is sitting on. The top row shows the cell in a low-viscosity fluid, and the cell is exerting very little pressure. The bottom row shows how the cell quickly spreads out and its pressure increases when it is immersed in a high-viscosity fluid, more like conditions within the body.



The Princess and the Philosopher

The legacy of René Descartes should include the contributions of his student, Elisabeth of Bohemia, in the development of his ideas.

Dana Mackenzie

Thirteen years ago, I wrote an article for *American Scientist* called "A Tisket, a Tasket, an Apollonian Gasket" (January–February 2010), which explored the fascinating mathematics and history behind a certain type of fractal foam—the "Apollonian gaskets" of the title. Recently, I've begun to see that history itself is like a fractal: When you take even the smallest event and magnify it, it springs to life and turns out to have a whole story of its own.

One sentence in particular from my article nagged at me: "In 1643, in a letter to Princess Elizabeth of Bohemia, the French philosopher and mathematician René Descartes correctly stated (but incorrectly proved) a beautiful formula concerning the radii of four mutually touching circles." This offhand comment is not really wrong but also not really right, and what's worse is that I had drawn the idea from articles by other scholars without looking into it critically. In fact, this one sentence raises all sorts of questions. Why was Descartes writing to a princess, and how did they get on the subject of circles? Why did he write to her about this problem, and not to the many other mathematicians he corresponded with? And who was Princess Elizabeth, anyway?

The answers to these questions reveal the foibles and personalities of two immensely fascinating people, René Descartes and Princess Elisabeth (who signed her name with an *s*). The true story of the formula is considerably more nuanced than its conventional name, *Descartes's circle theorem*, implies. It introduces a mathematician who has not been widely recognized for her mathematics. And it makes one think about why certain problems or theorems become famous. Histories and textbooks of mathematics tend to shine a spotlight on certain topics, but to understand why they mattered to the people who worked on them (and why they might still matter to us), you have to step outside of the spotlight so that you can see the shadows that define and delimit them.

Katherine E. Stange and Daniel Martin

This puzzle illustrates Descartes's circle theorem, which describes the specific conditions required to have four *mutually tangent* circles (circles that touch at just one point). Many such quadruples can be found in this puzzle, such as the circles labeled 11, 14, 15, and 86. These labels refer to the circles' curvatures, which are reciprocals of their radii ($^1/_{11}$, $^1/_{14}$, $^1/_{15}$, and $^1/_{86}$, respectively).

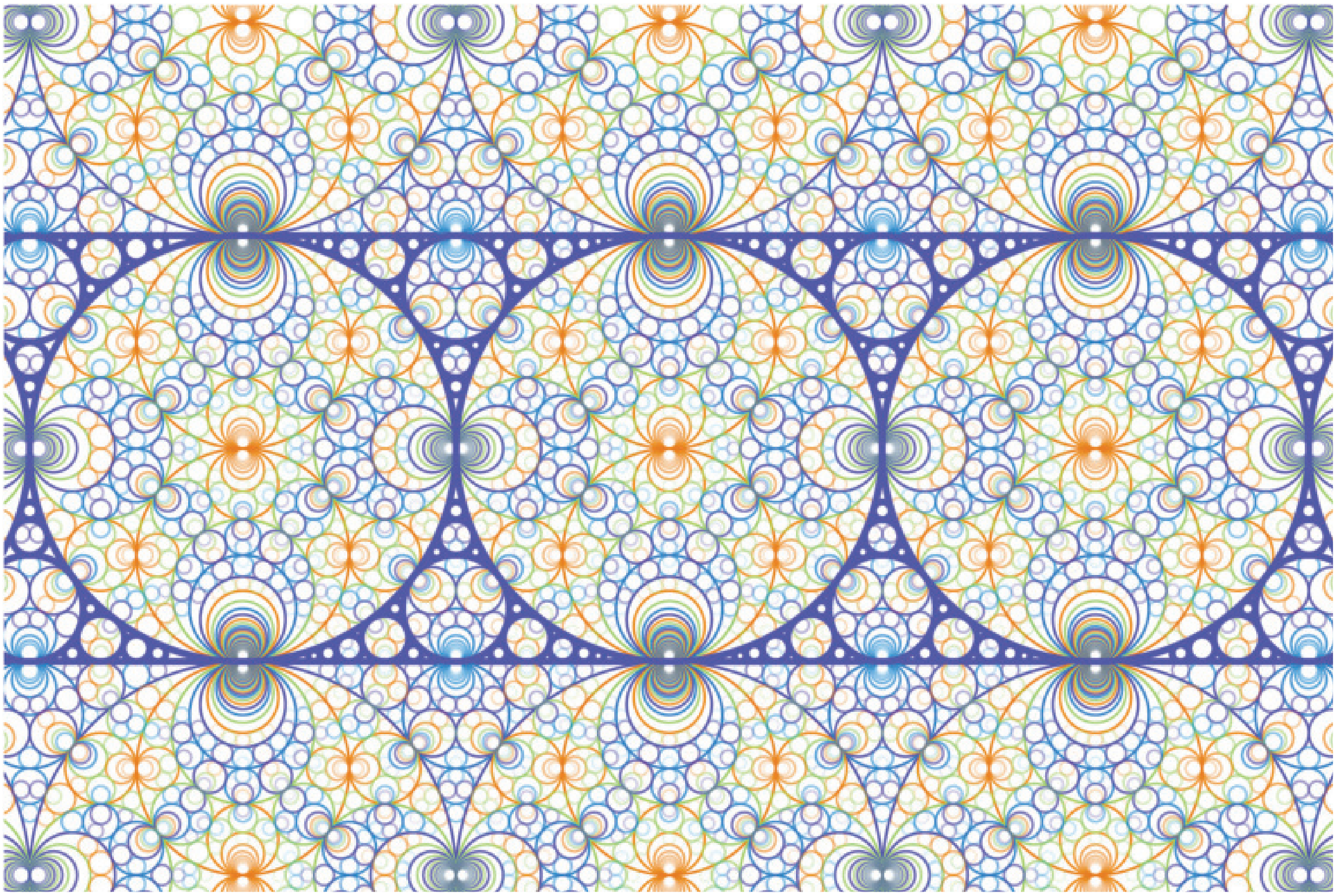
In an unusual twist, the mathematics is perhaps the least complicated part of this story. The formula proven by Descartes (who must have had a correct proof, in spite of what I wrote 13 years ago) relates the radii of the circles in any configuration of four circles that are *mutually tangent* (meaning each pair of circles touches at just one point). Descartes's circle theorem says that it is unusual to be able to arrange four circles in such a configuration, and it can be done if and only if their radii satisfy a particular formula. For example, in the puzzle shown above, the circles labeled 11, 14, 15, and 86 are mutually tangent. The

QUICK TAKE

René Descartes's correspondence with Princess Elisabeth of Bohemia may seem like a historical footnote, but their letters reveal her integral role in the development of his ideas.

Princess Elisabeth pushed Descartes to work his solution to the classical Apollonian circle problem through to the end. That exercise resulted in Descartes's circle theorem.

Reexamining the origin stories behind big ideas can complicate our understanding of how theories develop and lead us to reevaluate whom we lionize in the history of innovation.



Katherine E. Stange, University of Colorado, Boulder

This mandala-like figure created by mathematician Katherine E. Stange is a beautiful, computer-era take on René Descartes's circle theorem. An Apollonian gasket (*dark blue*) is formed by repeatedly inscribing circles into the gaps created by mutually tangent circles. Descartes's letters strongly suggest that he would not have developed his circle theorem without the contributions of Princess Elisabeth of Bohemia, his student. The 17th-century theorem became key to the study of Apollonian gaskets in the 20th century.

numbers represent the curvatures of the circles, which are the reciprocals of their radii ($^1/_{11}$, $^1/_{14}$, $^1/_{15}$, and $^1/_{86}$, respectively). The circles form a mutually tangent quartet because those curvatures satisfy the formula at the heart of Descartes's circle theorem: $(11+14+15+86)^2=2(11^2+14^2+15^2+86^2)$.

Descartes's discovery created a sensation because this theorem was related to one of the most famous problems of Greek antiquity. If you have three nontouching circles, exterior to one another, there is always a fourth circle that touches all three of them. A Greek mathematician named Apollonius, in the third century BCE, had supposedly solved the problem of how to construct this fourth circle using ruler and compass, but the book in which he wrote his solution had been lost. By 1600, this missing theorem was the Most Wanted Problem in European Mathematics. In that year, François Viète published a laborious solution. Forty-three years later, Descartes believed that his new approach to geometry (today called *Cartesian coordinates*) was so powerful that it would turn Apollonius's problem into one that an ordinary student could solve. Fortunately, he was blessed with a student who was anything but ordinary.

A Meeting of Minds

If I were writing this article in Europe in the 1600s, Princess Elisabeth Simmern van Pallandt of Bohemia and the Palatinate would need no introduction. She was the daughter of Frederick V, one of the seven electors of the Holy Roman Empire, and the granddaughter of King James VI and I, the first king of both Scotland and England. Her homeland, the Palatinate, was a state in what is now central Germany, with its capital in Heidelberg.

In 1620, two years after Elisabeth's birth, her family was driven into exile in The Hague, in the Netherlands, where they lived for three decades while the Thirty Years' War—a sprawling religious conflict—ravaged central Europe.

For a freethinking girl such as Elisabeth, The Hague was an ideal place to grow up. Thanks to her family's connections, she had access to the leading scholars of Western Europe. In 1634—at the age of 16!—she organized a debate concerning ways of knowing the Truth, and chose as speakers a Scottish minister named John Dury and an itinerant French philosopher who, like her, was living in exile: René Descartes.

Descartes would become world-famous three years later with the publication in 1637 of *A Discourse on the Method of Correctly Conducting One's Reason and Seeking Truth in the Sciences*. Although most of the world remembers his *Discourse* for its quote "I think, therefore I am" ("*Je pense, donc je suis*"), it was also a watershed book for mathematics. Descartes included a lengthy appendix called *Geometry* that, in effect, introduced the tool that we now call Cartesian coordinates.

Elisabeth and Descartes must have stayed in contact over the next few years, but their preserved correspon-

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In 1634, the 16-year-old Princess Elisabeth (*right*) invited Descartes (*left*) to participate in a debate on the nature of Truth. This meeting developed into a student–teacher relationship and a fruitful intellectual correspondence that lasted until Descartes's death in 1650. Although they mostly discussed questions of philosophy, on one memorable occasion they tackled a notoriously difficult math puzzle: the Apollonian circle problem.

dence starts abruptly in May 1643. At first, Elisabeth asked Descartes about philosophical questions, but later that year, their discussion turned to mathematics. She had been learning geometry from Descartes's friend, an Italian expatriate named Alphonse Pollot. But she must have realized that it made more sense to learn the new approach to geometry from the person who originated it, and Pollot was demoted from tutor to courier.

At some point that fall, Descartes assigned Elisabeth the Apollonian circle problem, the same problem that had been solved only four decades earlier by Viète. That solution used the traditional tools of ruler and compass that the ancient Greeks would have approved of. But Descartes wanted Elisabeth to use his new algebraic approach to geometry, not Viète's classical approach. Descartes was the first mathematician, indeed the first scientist, to think about the world in terms of coordinates (which is second nature to students today). He was certain that even this formidable ancient geometry problem would yield easily to his methods. It's clear that he did not actually try to solve the problem himself before assigning it to her, an omission born of hubris that he soon regretted.

A Method Goes Awry

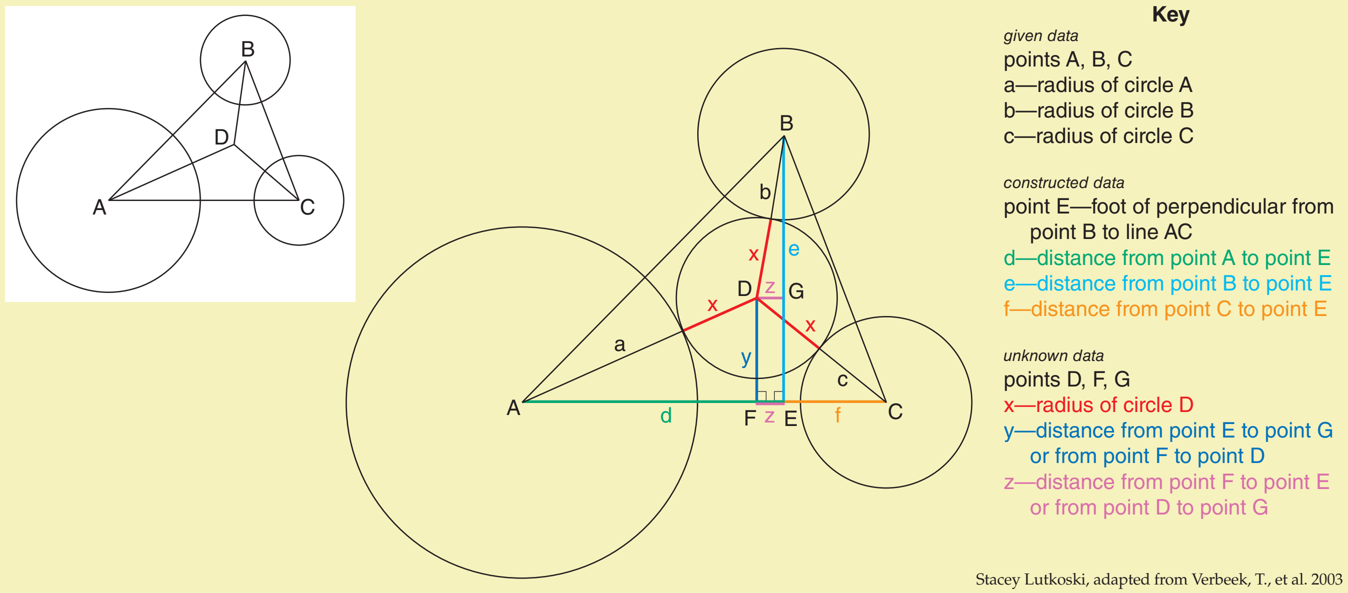
The first hint of trouble comes in a letter from Descartes to Pollot, dated November 17, 1643, in which Descartes frets that the problem is too hard. Descartes sends Pollot a sketch of his solution, but tells him not to give it to Elisabeth if she wants to continue working on the problem: "I ask you not to give her my letter so soon. I have left it undated."

For Descartes, the actual solution to the problem was not as important as the fact that he had produced an algorithm to solve it.

The undated letter is not a complete solution, but it shows how Descartes had thought the problem could be solved. He labels the centers of the three given circles as A, B, and C, and the center of the unknown fourth circle as D (*see page 83, inset*).

Because the three circles—A, B, and C—are given, Descartes assumes that we know their radii (a, b, and c). But we don't know the radius of the fourth circle, which Descartes denotes by x (*see page 83, colored diagram*). Descartes has drawn three auxiliary lines, BE (a perpendicular from vertex B to side AC), DG (a perpendicular from the unknown point D to BE), and DF (a perpendicular from D to AC). He also introduces two auxiliary variables: y, the length of EG, and z, the length of EF. To the untrained eye, the addition of these variables looks like a completely unmotivated trick. But to the trained eye, it is history in the making. Descartes is drawing a *coordinate system*, with E as the origin, EB as the y-axis, and EF as the z-axis. The numbers (y and z) are nothing but the coordinates of the unknown point D. Find y and z, and you solve the 1,900-year-old problem.

To Descartes, coordinates were not an unmotivated trick, but a systematic method for solving every problem in geometry. You introduce these new variables, write down everything you know about them in polynomial equations,



Stacey Lutkoski, adapted from Verbeek, T., et al. 2003

In Descartes's strategy for solving the classical Apollonian problem, circles A, B, and C are given (*inset*). He begins by dropping a perpendicular from point B to line AC, in effect defining Cartesian coordinates (*y* and *z*) for the unknown point D. However, the equations governing the unknowns—*x*, *y*, and *z*—are not readily solvable by hand. Descartes was forced to search for a more tractable version of the problem to satisfy Elisabeth's request for a theorem. This nudging from the princess resulted in the development of Descartes's circle theorem.

and then solve the equations. Geometry is completely reduced to algebra.

And yet, the devil is in the details—those pesky details that Descartes didn't bother to work through. Using a modern computer algebra program, Dutch math historian Henk Bos has shown that Descartes's three equations in three variables, x, y, and z, can be reduced to a single quadratic equation in one variable, but with 87 terms! In practice, solving such an equation would hardly be feasible for a student, or even for Descartes himself. By the time he wrote his undated letter, Descartes had realized this. "It is no longer necessary to go on," he wrote to the princess. "For the rest does not serve to cultivate or entertain the mind, but only to exercise one's patience for laborious calculations."

A mathematician bailing out on mathematics? What is going on here? I think I can explain. For Descartes, a big-picture guy, the actual solution to the problem is not as important as the fact that he has produced an algorithm to solve it. By reducing Apollonius's problem to quadratic equations, he has shown *in principle* that it is solvable with ruler and compass. His viewpoint is startlingly modern. In the computer era, an algorithm is very often the real prize, because any particular instance of the problem can then be solved by plugging in the data and running the algorithm on a computer.

Although I admire Descartes's vision, I nevertheless believe that he made a fundamental mistake. Yes, algorithms to solve problems are important. But sometimes the solutions themselves are also important. They can reveal phenomena or connections we did not expect, and lead us to deeper understanding. If you stop halfway and say, "I know how to do the rest," you miss out on that possible moment of discovery.

Descartes gave the nugget to Princess Elisabeth without ever suspecting that he had found a gold vein that would lead directly to 20th-century mathematics.

A Remarkable Save

While Descartes was conferring with Pollot, Elisabeth had been working on her own solution to the problem. Thanks to Descartes's letters, we know a good deal about how she proceeded. Notably, she did not introduce the extra variables y and z. Instead, she tried to solve the problem using only the variable x. Her solution could be viewed as a sort of hybrid, one that does not use Cartesian coordinates but does reduce the problem to algebra. She clearly made more progress than Descartes expected, and stopped only because she could not see the finish line. "For I well noticed that there were things missing in my solution, as I did not see it clearly enough to arrive at a theorem," she wrote on November 21.

Note the difference between Elisabeth's viewpoint and Descartes's! She wants to prove a theorem, a simple declarative statement that starts, "The radius of the fourth circle is . . . " She still belongs to the classical school, which sees the goal of math as a theorem, not an algorithm.

In fairness to Descartes, I should say that he understood both of these viewpoints. In his reply to Princess Elisabeth on November 29, he wrote: "Your Highness can see here two very different procedures for solving one problem, according to the different aims one has. For wanting to know the nature of the problem, and by what device one can solve it, I take as given perpendicular or parallel lines, and suppose more unknown quantities." (He is clearly describing his own approach to the problem.) "On the other hand, in wanting to find the solution, I take as given the sides of the triangle and suppose but one unknown letter." (Here, he is describing Princess Elisabeth's solution.)

Now comes the moment when Descartes impresses me most. Remember, he never did have a complete algebraic solution to Apollonius's original problem. Now Princess Elisabeth called his bluff: She wanted to know what the theorem should say, so that she could try to prove it. Somehow, over the course of eight days (or less, depending on the speed of Pollot's courier service), Descartes figured out that there is a special case of the problem in which the equations dramatically simplify. In fact, they simplify to such an extent that one might justifiably call it a theorem (and posterity has decided to call it Descartes's circle theorem). In his November 29 letter, he sends her this revised version: "If your Highness has the desire to try it, it will be easier for her to suppose that *the three given circles touch one another* . . . " (My emphasis added.)

In this moment, history tiptoes in through the back door. Remember that Apollonius had made no such assumption. We have here a new version of the problem, which I call the *refined* Apollonian problem. This version is easier because you have an extra assumption to work with. But, paradoxically, I would say that this "easier" version is the only version of the Apollonian problem that mathematicians still care about today. The reason is that the refined Apollonian problem is infinitely extensible. After you construct circle D, you will notice that you have created three new triangular "pockets" into which you can inscribe three new circles, whose radii you can compute by again using Descartes's formula. By repeating this process ad infinitum, you obtain an Apollonian gasket. These fractals have remarkable kinds of symmetry that had never been observed before, which combine the geometry of the circles with the algebra relating their radii (a direct consequence of Descartes's circle theorem). Although it is difficult to portray this symmetry in a picture, the mandala-like diagram by mathematician Katherine E. Stange of the University of Colorado, Boulder, comes close (*see image on page 81*). Stange has color-coded the circles according to their radii, using a simple algebraic rule that, in my view, turns a simple geometric diagram into art.

To sum up: At some point in those eight days, Descartes swung his pickax and out popped a gold nugget. But he did not realize what he had discovered! He gave the nugget to Princess Elisabeth without ever suspecting that he had found a gold vein that would lead directly to 20th-century mathematics.

Philosopher and Mathematician

In recent years, feminist philosophers have begun to reevaluate Princess Elisabeth as a philosopher in her own right, not just an acolyte of Descartes. In her letters, she was constantly probing and challenging her ostensible mentor. Descartes, unusually for him, graciously acknowledged her contribution. Dedicating one of his books (*Principles of Philosophy*, 1644) to her, he wrote:

> I have even greater evidence of your powers—and this is special to myself—in the fact that you are the only person I have so far found who has completely understood all my previously published works. . . . It generally happens with almost everyone else that if they are accomplished in Metaphysics they hate Geometry, while if they have mastered Geometry they do not grasp what I have written on First Philosophy. Your intellect is, to my knowledge, unique in finding everything equally clear.

Elisabeth was not a passive recipient of Descartes's letters. Descartes would never have discovered his circle theorem if it had not been for her prodding.

After Descartes's death in 1650, Elisabeth stayed in contact with several other mathematicians. She never married and instead entered Herford Abbey, a Lutheran religious community, where she rose to the level of abbess in 1667. While there, she remained in contact with the European mathematical community, even transcribing and sharing her letters from Descartes about the Apollonian circle problem.

We find her being mentioned with respect by other mathematicians of the time, several of whom wrote to request her help in understanding Descartes's *Geometry*. In 1657, one of those correspondents, English mathematician John Pell, cast shade on another scholar who claimed to be the best mathematician in Heidelberg: "I hope he did not profess himself such, whilest the Princess Elizabeth was in Heidelberg. Now shee is gone; he may, perhaps justly, say, that he understands Des Cartes better than any Hee or Shee in that University."

Clearly, Princess Elisabeth's peers recognized and respected her as a mathematician, but she is somehow missing from most accounts of early modern mathematics. Elisabeth has been reduced to a footnote of Descartes's work, but she was not just a passive recipient of his letters. Descartes would never have discovered his circle theorem during those eight days, or even thought about the refined Apollonian problem, if it had not been for her prodding. She was the one who tried the one-variable approach. She was the one who wanted to prove a theorem, rather than just wave her hands and say the problem was done.

But beyond issues of credit, the story of the princess and the philosopher appeals to me because it is, at heart, an ordinary story that took place in such extraordinary circumstances. Theirs was the perfect student–teacher relationship, in which "student" and "teacher" melted away and became "colleagues." Just as the beauty of Descartes's theorem appears in the gaps between circles, the beauty of history—the human relationships—emerges when you peer into the gaps between the bare facts.

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Dana Mackenzie is a mathematician who went rogue and became a science writer. His previous article on Apollonian gaskets (January–February 2010) was awarded the 2015 Chauvenet Prize for mathematical exposition from the Mathematical Association of America. Email: scribe@danamackenzie.com

Technologue

The Right Mount

How and where engines are affixed to aircraft wings can be a complex challenge.

Lee S. Langston

Whenever I get a window seat on a large airplane, the view of a mighty jet engine mounted under the wing in flight is an awe-inspiring sight for me—especially during rough weather that can noticeably deflect the wing. I marvel at the engineering required for the engine mounts to keep the engine safely attached, while simultaneously transmitting thrust for flight, carrying engine weight, and supporting the aerodynamic forces buffeting the engine's housing, called a *nacelle.*

The first commercial jetliner, the 1947 de Havilland DH.106 Comet, had its engines embedded into its wings, at the base near the fuselage of the airplane. But a year before, Boeing had developed a bomber (its Model 450, which became known as the B-47 Stratojet) that had jet engine pods hung on thin struts called *pylons*, well below and ahead of the wing's leading edge. Since then, airline designers have largely followed the Boeing stratagem of underwing engine mounting.

Engine mounts have a complex job. The thrust forces that move the aircraft, generated by gas flow changes in a jet engine, are transmitted by pressure and friction forces onto components and struts attached to the engine case. Case engine mounts then transmit the thrust forces (as high as 100,000 pounds or 445 kilonewtons of force on the largest engines) to the wing pylon mounts, to pull the plane forward. The mounts must also support the engine's weight (as much as 20,000 pounds or about 9,000 kilograms) and carry the load of aerodynamic forces on the nacelle during flight. Because engine casings experience wide variations in temperatures and loads, some engine mounts incorporate an ability to move, to allow the casings to expand and contract freely in both axial and radial directions. All of these factors add up to a wide range of variables that must be within strict parameters, or the results can be catastrophic.

Mounting Troubles

Engine mounts were indirectly involved in two fatal crashes of the Boeing 737 MAX, an aircraft that was introduced after its certification by the Federal Aviation Administration in March 2017. One crash occurred on the edge of Indonesia's Jakarta Bay after takeoff of Lion Air Flight 610, on October 29, 2018, killing all 189 people on board. The second crash took place on March 10, 2019, again on takeoff, from Addis Ababa, of Ethiopian Airlines Flight 302, killing all 157 people on board.

These two crashes, which claimed a total of 346 lives, resulted in the worldwide grounding of the 387 existing 737 MAX aircraft by March 18, 2019. Subsequently, after better documentation and training for pilots and costly work to fix contributing operational and design problems, regulatory bodies allowed MAX commercial flights to resume in late 2020 and early 2021. As of January 2023, Boeing was required to appear in court to face the families of victims of those crashes, who are challenging the settlement that the American government reached with the company.

In addition to the tragic loss of human life, this dire series of events has presented a major financial hit to Boeing, as well as inflicting reputational harm on the company, revered for its long and successful aviation history. Estimates vary, but the accidents and grounding costs to Boeing may be $20 billion or more, with indirect costs as high as $60 billion from canceled MAX orders.

The original Boeing 737, first flown in 1967, is an almost 60-year-old design. After resolving some initial design hiccups, it has proven to be the most popular twin-engine airliner, with the 10,000th 737 rolling off Boeing's Renton, Washington, production line in 2018, powered by CFM International's CFM56 engines. The CFM56 turbofan engine has a 60-inch (152-centimeter) fan diameter. Power and fuel efficiency in turbofan engines are determined by what is called the *bypass ratio*, the mass of air bypassed around the engine for every unit of mass of air through the engine (*see "Gears Drive the World," Technologue, March–April 2022*). The CFM56 has a bypass ratio of 5:1. The nacelle inlet shape on the 737 is flattened on the bottom, a design consideration that allows it to use a larger engine while maintaining a required taxiing ground clearance of 17 inches (43 centimeters). The airline industry has given the flattened shape of this engine opening the nickname of "hamster mouth" (*see figure at the top of page 88*).

QUICK TAKE

Aircraft engines are usually mounted on thin struts called *pylons* so that they hang below and in front of a plane wing's leading edge, a position that has been popular since the 1940s.

Engine mounts have the task of holding the engine on the plane, while also transmitting thrust forces and allowing for movement caused by temperature and force fluctuations.

Design considerations on the placement of engine mounts have had unintended consequences, such as aircraft handling problems and physical distortion of engine cases.

Uwe Deffner/Alamy Stock Photo

The Boeing 737 MAX made a triumphant debut at the Farnborough International Airshow in the United Kingdom in 2018, but the model was soon grounded after two fatal crashes that occurred in the months that followed. The 737 MAX updated the earlier 737 design with larger, more fuel-efficient, and quieter engines, but their size necessitated that the engines be mounted higher and farther forward, adversely affecting aircraft handling during certain flight conditions. The problem was addressed only with software, which had system flaws.

In the quest for greater fuel economy, the 737 MAX had the CFM56 engine replaced with CFM International's new LEAP turbofan. LEAP (for Leading Edge Aviation Propulsion) has a bypass ratio of 9:1 (and thus higher fuel economy) and a 69.4-inch (176.3-centimeter) fan diameter, providing more power.

With the increased fan size, the LEAP engine nacelle had to be mounted slightly higher and further forward on the wing from the previous CFM56 engines, to give necessary ground clearance. But an unintended consequence of this new location and larger nacelle is that during flight, it causes air vortex flow off the nacelle body, which produces unwanted lift at high flight angles, especially during aircraft climb at takeoff. Because the LEAP nacelle is in front of the plane's center of gravity, this unintended nacelle lift causes a slight effect in which the nose of the aircraft pitches up. If sustained, this pitch-up brings the aircraft closer to stall and causes a devastating loss of aircraft lift. (*See "Averting the Pall of Stall," Technologue, January–February 2020.*)

Having some background as a gas turbine aerodynamicist, I would have expected Boeing to eliminate the unwanted nacelle lift directly. That process might have entailed changes to the surface of the nacelle to break up the vortex airflow, and extensive wind-tunnel testing.

But instead of aerodynamic fixes for this unwanted LEAP nacelle lift, Boeing engineers created an automated anti-stall system, called MCAS (for Maneuvering Characteristics Automation System). This software code expands how the 737 MAX tail-mounted horizontal stabilizer is automatically adjusted to counter the unwanted nacelle lift. This flight control software depends on a sensed flight angle (called the *angle of attack*) from a fuselage-mounted sensor (*see figure on the bottom of page 88*). Malfunction of the sensor combined with MCAS system flaws are what led to the two 737 MAX fatal crashes.

The 737 MAX MCAS controls fix that was chosen by Boeing may have been more expedient, but it cost many lives and could cost the company more in the long term.

Solving Distortion

Although many of the engineering details behind the LEAP engine mounting troubles are still proprietary, other cases can provide insight.

I can give a more detailed, first-person account of an earlier episode of engine mounting troubles, this time involving the iconic Boeing 747. With its maiden flight on February 9, 1969, Boeing's four-engine 747 was the first commercial jumbo jet. It is the most successful wide-body passenger aircraft yet developed, with more than 1,500 produced to date; its more than a half-century production run at Everett, Washington, ended in 2022.

As a young engineer in the 1960s at Connecticut's engine company, Pratt & Whitney Aircraft (now Raytheon Technologies' Pratt & Whitney), I had some personal involvement with solving engine mounting troubles with the 747's inaugural engine, the PWA JT9D.

Less than six months after its maiden flight, it was determined that the JT9D engine case was excessively bending and ovalizing—distorting into a non-circular shape—under thrust loading that could be as high as 43,500 pounds of force (194 kilonewtons) during takeoff. The ovalizing distortion resulted in turbine and compressor blades rubbing against the interior of the engine case and necessitated power-robbing increases in

Leeham News

The original 1960s Boeing 737 had a smaller JT8D engine with a cylindrical nacelle, but was replaced with the larger CFM56 engine nacelle (*left*) that was redesigned to have a flattened bottom to increase clearance, leading to its nickname of having a "hamster mouth" shape. When the aircraft was redesigned as the 737 MAX, the LEAP engine used (*right*) was more fuel efficient and quieter, but its larger size meant it had to be mounted farther forward and higher than before, causing the possibility of aircraft stall under certain flight conditions. Instead of redesigning the engine nacelle's shape this time, fixes were made with software.

blade tip clearance gaps. The result was a serious reduction in thrust, and increased fuel consumption, as much as 7 percent above what the manufacturer had guaranteed.

Both Boeing and Pratt & Whitney were essentially betting their net worth on the 747. At one time, there were 15 four-engine 747 jets sitting engineless on Boeing's Everett tarmac, representing \$360 million—or more than \$2 billion in 2023 dollars—of stranded assets. Getting those planes into the air was an engineering and commercial imperative. As *Time* magazine reported in September 1969:

> On the apron outside Boeing's plant in Everett, Wash., 15 enormous 747 jets stand high and silent, harbingers of a new era in aviation. They are painted in the colors of several international airlines: TWA, Pan Am, Lufthansa, Air France. For the moment, however, the planes are the world's largest gliders—because they have no engines. Pan Am had been scheduled to get the first three commercial giants, each with a capacity of 362 passengers, in late November. Last week embarrassed Boeing officials said that performance difficulties in the Pratt & Whitney JT9D engines would delay that delivery as much as eight weeks.

When a major problem like this occurs, an engine company will try multiple paths to find the cause—and the cure. In my own case, I worked with an engineering team on an investigation of possible thermal effects that might be causing the engine case distortion. This multiple-path approach ended when it became clear that the distortion was a structural problem, caused by the position of the main thrust mount on the turbine case.

Pratt & Whitney structural engineers then conducted extensive static JT9D case deflection tests and analysis. They found that if two—rather than one—thrust mounting points were circumferentially located 90 degrees apart at any one axial position on the engine case, the resulting ovalization of each would cancel the other, greatly reducing overall case distortion. This two-point distortion canceling method was very effective, so much so that the results were extended to show that the two mounting points could be separated by as much as 120 degrees and still yield an acceptable amount of case distortion reduction.

The Pratt & Whitney team then devised and designed a Y-shaped titanium tubular thrust frame with arms that were fastened to the case around the compressor at two fixed mounts, about 120 degrees apart. The leg of the thrust frame then attached to the rear turbine case mount through an axially sliding joint, to accommodate engine axial length changes, and that mount was rigidly affixed to the pylon.

In the continuous pursuit of airline fuel economy, engine fan sizes are ever growing, and safely mounting engines under a wing will remain a daunting task.

Subsequent engine tests showed that the new thrust frame substantially reduced ovalization. Maximum thrust could be achieved with little case distortion, and engine performance now met

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A software system in the 737 MAX was designed to prevent the craft from going into stall at high angles of flight, such as during takeoff. The position of the airplane's engines, with nacelle aerodynamic forces forward of the plane's center of gravity, could cause the plane's nose to pitch upward during such high-angled flight. The software system depended on sensors in the nose of the plane (*left*) to detect the plane's angle of flight. Flaws in both the sensors and the software led to two fatal crashes.

Photo 12/Alamy Stock Photo

An October 1969 photo shows one of the first Boeing 747 airplanes being assembled at the Boeing plant in Everett, Washington. Production had been delayed by problems with distortion in the engine case that was causing the blades to wear out, as well as costing a reduction in both thrust and fuel efficiency. The problem was repaired by developing a Y-shaped mount that stabilized the engine case and prevented the shape distortion.

guaranteed fuel consumption specifications. The new thrust frame (which became known as the "yoke" at Pratt & Whitney) added about 163 pounds (74 kilograms) of weight to the 8,600-pound (3,900-kilogram) JT9D, and required a relocation of several external engine components. But as an add-on, the frame didn't necessitate an additional FAA certification of the engine, and it solved the ovalization problem that was threatening the financial future of both Boeing and Pratt & Whitney Aircraft.

The mounting of jet engines continues to challenge airframe and turbofan jet engineers. For proprietary reasons, not much is published in the open literature, but patent listings give an idea of the ongoing technical activity in jet engine mounting.

In the constant pursuit of airline fuel economy, engine bypass ratios are increasing (12:1 on new geared fan engines), with fan sizes ever growing (178 inches [452 centimeters] on the new General Electric GE9X turbofan engine). Safely mounting engines under a wing will remain a daunting task.

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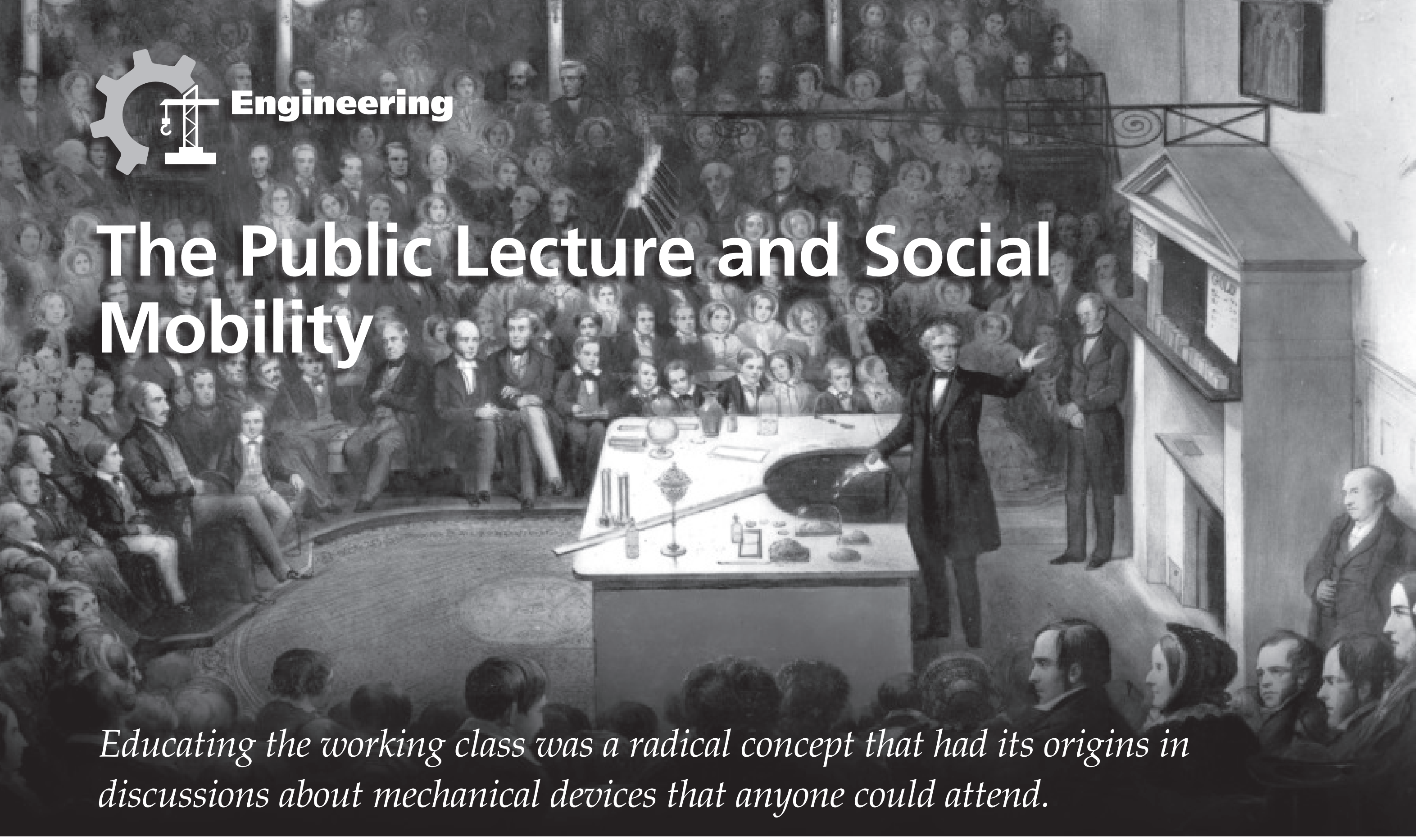
Lee S. Langston is a professor emeritus of mechanical engineering at the University of Connecticut. He regularly writes articles on gas turbine technology. Email: lee.langston@uconn.edu

Engineering

The Public Lecture and Social Mobility

Educating the working class was a radical concept that had its origins in discussions about mechanical devices that anyone could attend.



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Michael Faraday is shown here delivering a lecture during the 1855–1856 holiday season at the Royal Institution. Faraday designed his lectures to be publicly accessible even to children. This audience included Great Britain's Prince Albert and one of his children, Prince Alfred.

Henry Petroski

Engineering as a profession was in its infancy in the late 18th century in Great Britain. Up to that point, working-class mechanics, who were accustomed to using their ingenuity and self-study to solve problems, effectively fulfilled the need for engineers. But as the Industrial Revolution led to the proliferation of newly conceived mechanical devices and structures, as well as factories that ran on them, there was a pressing need to develop a formal system of education to train engineers to serve the growing British commercial economy.

In 1800, prior to practicing as a physician, George Birkbeck accepted the position of professor of natural philosophy at the Andersonian Institute in Glasgow, now the University of Strathclyde. When mechanics attending his lectures at the institute began asking about the apparatus he used in his demonstrations, Birkbeck conceived of the idea of offering free public lectures on mechanical arts to expand their knowledge and provide intellectual stimulation. In 1804, after his fourth and last annual lecture in Glasgow, which drew an audience of 500, he left for London, but the practice of offering public lectures had taken root. In time, this concept led to the idea of establishing mechanics' institutes; Birkbeck founded the London Mechanics' Institute in 1823. Scotland also saw the establishment of institutions such as the Edinburgh School of the Arts, which was founded in 1821 and later developed into Heriot-Watt University. The first lecture presented at the Edinburgh school, on chemistry, had 452 attendees. The stated purpose of the school was to "address societal needs by incorporating fundamental scientific thinking and research into engineering solutions." Throughout the 1820s and 30s, mechanics' institutes sprang up throughout Britain and its empire. The movement to equalize access to education was not without controversy: An editorial in the *St. James's Chronicle* in May 1825 said of the foundation of the London Mechanics' Institute that "a scheme more completely adapted for the destruction of this empire could not have been invented by the author of evil himself." But the success of the institutes soon outstripped any naysaying.

In 1799 the Royal Institution of Great Britain had been founded in London "to introduce new technologies and teach science to the general public through lectures and demonstrations." These lectures became so popular that on days they were given, the volume of associated carriage traffic led to making Albemarle Street, onto which the Institution's building fronted in London's fashionable Mayfair district, the city's first one-way street. Michael Faraday, having completed a seven-year apprenticeship to a London bookbinder and bookseller, which had given him the opportunity to read widely and develop an interest in chemistry and electricity, attended lectures in chemistry given by Humphrey Davy. Faraday's notes formed the basis for a book he later wrote and sent to the lecturer. Davy was very impressed and, despite Faraday having had no formal education, took him on as an apprentice. After Davy's eyesight was compromised in an accident, he made Faraday one of his assistants. In 1813, Faraday was appointed

Henry Petroski is the A. S. Vesic Distinguished Professor of Civil Engineering Emeritus at Duke University. His new book is Force: What It Means to Push and Pull, Slip and Grip, Start and Stop (*Yale University Press, 2022). Email: petroski@duke.edu*

as a chemical assistant at the Royal Institution, and in 1821 he was elevated to Assistant Superintendent of the House.

In 1825, Faraday established the Institution's Christmas Lectures, so named because they were offered over the school holiday season. Except for a hiatus during World War II, the lectures continue to this day. Faraday himself lectured for 19 seasons, including every one during the decade of 1851 to 1860, on such topics as chemistry, electricity, and force. Londoners of all ages and genders were enthusiastic attendees. Over the 1859–1860 holiday period, Faraday gave "a course of six lectures on various forces of matter and their relations to each other." In his introductory remarks to the series opener—on gravitation—he addressed specifically the younger people in the audience and, "as an elderly, infirm man," told them that preparing the lecture had enabled him to "return to second childhood, and become, as it were, young again among the young." One attendee recalled Faraday's "silvery hair" and "earnest face."

The next season, at the age of 69, Faraday gave his last and most famous set of lectures—on the nature of a candle and its flame that burned and flickered between him and the capacity audience of 700. Tickets to the event were so hard to come by that Faraday himself could not supply one to a friend. In that series, Faraday spoke in detail about a candle's wax, wick, and smoke, and the differently colored regions of the flame.

Just as the lectures on force were captured by a "careful and skilful reporter" and "printed as they were spoken, verbatim et literatim," so too the words of Faraday's "irresistible eloquence, which compelled attention" on the chemical history of the candle were "recorded verbatim." And because the talks were directed to young people, they were "as free as possible from technicalities," and so required no prerequisite knowledge of the subject. But they did deal with concepts that were much more than trivial.

The layout of the lecture room at the Royal Institution was captured in many drawings, paintings, and photographs. A rather detailed sketch by the Scottish portrait painter Alexander Blaikley showed Faraday delivering a lecture during the 1855–1856 season, which was attended by Prince Albert and his young son, Prince Alfred, sitting front and center. The horseshoe shape of the table behind which Faraday stood allowed him to easily reach the many props and pieces of apparatus spread out before him. These items were integral to the lecture, and their function and relevance to the topic were revealed as the lecture progressed. If Faraday did not have a particular item he needed for a lecture, he would invent it, as he did when he needed a supply of hydrogen at hand for an experiment in 1824. By fabricating a bladder out of the "exceedingly elastic" natural rubber called *caoutchouc*, known today as latex, he came up with an ad hoc device that earned him credit for having invented the toy balloon.

Tools of the Trade

Famous public lecture venues were not limited to London. In 1868, Thomas Huxley, the biologist, anthropologist, and staunch supporter of Charles Darwin's theory of evolution, delivered a lecture to a working-class audience in Norwich. He began his famous "On a Piece of Chalk" lecture by holding up a lump of carpenter's chalk and proceeding to discourse on the geological history of Britain, including the nature of the White Cliffs of Dover and the Chalk Marl formation beneath the channel between England and France. A century later, experimental psychologist Dael Wolfle described Huxley's lecture as an outstanding exemplar of "the art of explaining in compelling and understandable terms what science is about… [a] vigorous example of the scientist's obligation to practice that art." To Huxley, it was "nothing but trained and organized common sense," and so a lecture on science should be accessible to a general audience. The same may be said of any discussion on engineering.

Tickets to Michael Faraday's 1860 Christmas Lecture were so hard to come by that Faraday himself could not supply one to a friend.

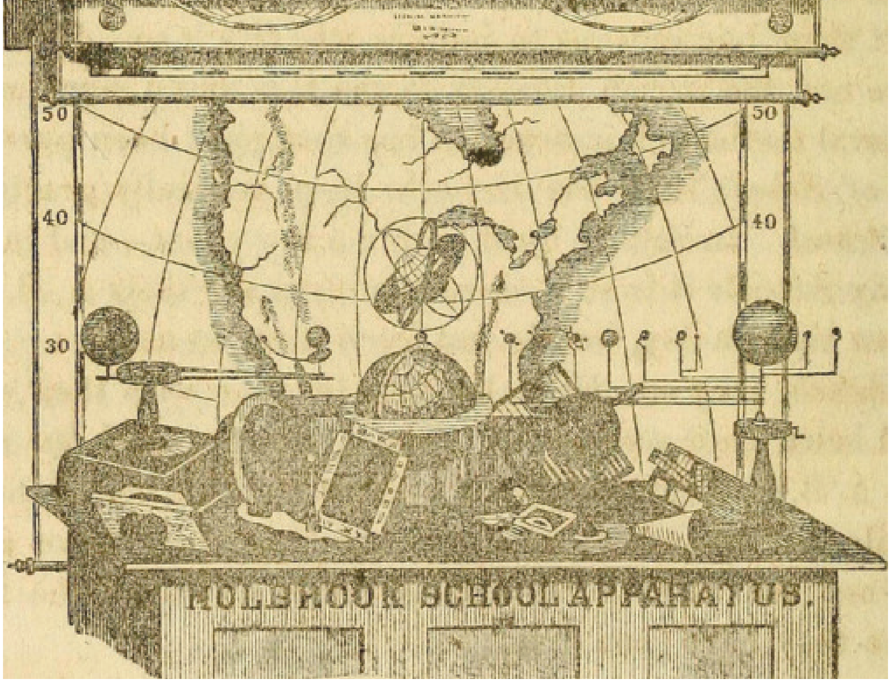
Scientific topics may have dominated the Christmas Lectures in particular, but the feats of Victorian engineers lionized by Samuel Smiles in his *Lives of the Engineers* (*see "Engineering," September–October 2004*) also captivated Victorians of all walks of life. Among the most dramatic construction projects of the mid-1800s were structures of novel design: the Britannia Tubular Bridge in Wales—which drew large crowds to the banks of the Menai Strait to watch critical steps in its erection, and even to pitch in to provide muscle power when things went awry (*see "Engineering," May–June 1992*)—and the Crystal Palace, the massive iron-and-glass building being erected in London's Hyde Park to house the Great Exhibition of 1851. Before it was filled with "the works of industry of all nations," the skeletal frame of the Palace served as the venue for a lecture on the structural principles behind such ambitious projects. As a surviving illustration of the lecture shows, the audience consisted of men, women, and children standing before a dais on which the lecturer used scale models as visual aids.

An early type of image projector, the magic lantern, also complemented the words and actions of public lecturers. Among the most enduring images projected in the late 19th century was that of the unprecedentedly large cantilever bridge under construction across the Firth of Forth near Edinburgh. The cantilever method of construction was virtually unheard of in Britain at the time, and this novelty, coupled with the prior failure of a bridge across the Firth of Tay near Dundee, which was on the same railroad line, called for reassuring the public that the tragedy would not be repeated. That task fell to Benjamin Baker, the engineer who had designed the Forth Bridge, who gave lectures at the Royal Institution and other venues. To give his audiences a feel for the structure, he and his colleagues devised a living model of the bridge that has become a classic in explaining the forces in a static structure (*see "Engineering," March–April 2013*).

Meanwhile, in America, public lectures and organizations sponsoring them were proliferating. An 1857 issue of *Putnam's Monthly Magazine of American Literature, Science and Art* declared:

> The Lyceum is the American Theatre. It is the one institution in which we take our nose out of the hands of our English prototypes—the English whom we are always ridiculing and always following—and go alone. The consequence is, that it is a great success. It has founded a new profession.

The word *lyceum*, which originally designated the Athenian garden where



The Reading Room/Alamy Stock Photo

Teacher and traveling lecturer Josiah Holbrook established the *lyceum* movement in America in 1826, and also created teaching aids for these public classes, such as the ones illustrated here.

Aristotle taught, came to mean in the mid-19th century a literary institution, lecture hall, or teaching place. The origins of the movement to establish lyceums in the United States, especially in the Northeast and Midwest, can be traced to the teacher and traveling lecturer Josiah Holbrook, who established America's first industrial school in 1819, and its first lyceum in 1826. He was the founder of the Holbrook School Apparatus Manufacturing Company, whose products included objects to aid in the teaching of science in lyceums and public schools alike.

By one estimate, in the early 1840s as many as 4,000 communities had an organization of some kind sponsoring public lectures. Indeed, a lecture society was often among the first institutions formed in a newly founded town. Davenport, Iowa, serves as an example. It had a lyceum in 1839, the same year it received its charter and just three years after it had been laid out. At the time, its population was only 250. By the mid-1840s, few towns in the North with populations of 1,000 or more did not have at least one sponsor of public lectures. Although the lyceum movement was endorsed most notably by literary figures such as Ralph Waldo Emerson and Henry David Thoreau, the range of topics was eclectic. The 1851–1852 season in Belfast, Maine, for example, included lectures on astronomy, biology, geology, and physiology, in addition to conversation, reading, and the equality of the human condition.

Engineering and technology subjects were more commonly sponsored by the mechanics' institutes, which had taken root in America concurrently with the British movement. The General Society of Mechanics and Tradesmen of the City of New York was founded in 1785 by the city's skilled craftsmen. According to its current website, the organization "continues to serve and improve the quality of life of the people of the City of New York through its educational, philanthropic, and cultural programs, including its tuition-free Mechanics Institute, the General Society Library, and its century-old Lecture Series." On the West Coast, San Francisco's Mechanics' Institute dates from 1854, when the gold rush fueled the city's rapid population growth but left countless would-be millionaires desperate for a means of starting over. At a time when the state of California did not have a university or public library, the establishment of the mechanics' institute "with four books, a chess room, and a mission to start a vocational school," was a godsend. I have lectured at both these mechanics' institutes, and I can attest to the fact that each appears to be quite alive and well.

The seal of the New York mechanics' institute is dominated by iconography of a muscular arm and raised hammer that are said to be those of Vulcan, who in Roman mythology was the god of fire and metalworking. In 1867, the owner of the Vulcan Spice Mill in Brooklyn, New York, took the Vulcan arm and hammer as the trademarked logo of a newly formed baking soda company, which in time became Arm & Hammer. The logo was said to represent the "power" behind the baking soda's ability to "force" dough to rise. As businesses evolve, so do institutions. Although mechanics' institutes supplemented apprenticeships, and through their libraries provided resources for the self-study of engineering, the increasing complexity of technological systems demanded a more systematic approach to learning. Thus arose the so-called polytechnics, from which would descend such distinguished engineering schools as Rensselaer and Caltech. With the financial encouragement of the Morrill Land Grant College Act of 1862, known familiarly as the Morrill Act, the federal government helped states establish colleges that specialized in "agriculture and the mechanic arts." Many engineering schools, such as Texas A&M, make explicit in their name their status as land-grant colleges. Others, such as the University of Illinois, do not reveal that status in their name but rather in the presence of extensive research farms around their liberal arts and sciences campuses. There are also hybrid institutions: Cornell University, for instance, is part Ivy League and part land-grant college. The latter contains its engineering school.

Captured for Posterity

Today, institutions of higher learning of all kinds sponsor public lectures, often in a series named for a generous alumnus or benefactor whose endowment provides sufficient investment income to pay honoraria for distinguished speakers, not to mention attractive hors d'oeuvres for receptions afterward. Princeton is among the many elite colleges and universities that have an exceptionally large number of public lecture series. Sometimes, a course of lectures given by a speaker is subsequently published in book form, as my *Success Through Failure* was. The tradition harks back to Faraday's *Chemical History of a Candle* and Huxley's *On a Piece of Chalk*. These classic contemplations on a common object were inspirational to me in writing my book *The Pencil*.

Scientists and engineers do not often write out their lectures in detail beforehand, relying on the logical steps in the development of a mathematical demonstration or the rational progression of a technical argument to serve as prompts. In such cases, a manuscript of the lectures must be prepared in retrospect, which has the benefit of incorporating any incisive discussion with the audience. Today, instead of having a

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A section of the Chautauqua Institution's amphitheater shows the thousands in attendance in 1914, with programming that aimed to provide intellectual as well as moral self-improvement.

reporter take down verbatim the text of a lecture, it can be recorded. The British Institution's Christmas Lectures were first broadcast in 1936; they are also the oldest science television series, having been broadcast by the BBC since 1966.

When the topic of public lectures arises today, the TED Talks series often comes to mind. In fact, this series has its roots not in enlightening the pubic but in informing the elite, especially those associated with the Silicon Valley, Hollywood, and Madison Avenue cultures. The idea originated with Harry Marks, an accomplished "broadcast designer." He and Richard Saul Wurman, an architect and graphic designer, established the concept of conferences based on what Marks perceived to be a growing interrelationship among the fields of technology, entertainment, and design (or TED). The first TED conference was held in 1984 and featured demonstrations of the compact disc and the new Apple Macintosh personal computer. Attendance was limited to members of the TED Conference organization, to which membership was gained by registering for a TED conference. Although registration fees were steep, the conference was not a moneymaker. The second conference, held in 1990, was more promising and led to annual conferences with increasingly large numbers of fee-paying attendees, which taxed the capacity of the original Monterey, California, venue, driving TED to Long Beach and, later, to Vancouver, Canada. Attendance became by invitation only, and registration fees increased from $4,400 in 2006 to $6,000 the following year, and to $10,000 in 2018. The steep fee allows the attendee to participate in the accompanying exhibition of products and services, making the conference part trade show.

In 2007, when TED Talks (with the slogan "ideas worth spreading") did become freely available to the public via the internet, audiences of about 800 at the live annual conference grew in five years to a billion cumulative views of the virtual talks. Free live TED-like experiences began in 2009 with the availability of licenses to hold TEDx events, in which speakers follow the TED lecture model but cannot be compensated, the organizing group may not make a profit, and the copyright to the 18-minute talks must be assigned to TED, for them to be edited and distributed as TED pleases. TEDx has the cache of its big brother, and it does make public lectures available to local and regional audiences, but at a price.

The old-fashioned public lecture—held before a live audience of people from all walks of life—still exists, particularly at the Chautauqua Institution. *Chautauqua* is an Iroquois word that describes the pinched shape of the lake in upstate New York—about 80 kilometers southwest of Buffalo—which is the institution's venue. The Chautauqua movement traces its roots to 1874, when Methodist minister John Heyl Vincent and businessman Lewis Miller rented a Methodist camp meeting site to hold a summer training program for Sunday school teachers. From this start grew the nondenominational Chautauqua Institution, which soon was sponsoring adult education generally, including a correspondence-school effort known as the Chautauqua Literary and Scientific Course, to bring "a college outlook" to people of the working and middle classes. According to the institution's website, by the end of the century, the movement "was nationally known as a center for rather earnest, but high-minded, activities that aimed at intellectual and moral self-improvement and civic involvement." President Theodore Roosevelt called it "a source of positive strength and refreshment of mind and body to come to meet a typical American gathering like this—a gathering that is typically American in that it is typical of America at its best." At its peak of popularity, which occurred around 1915, Chautauquas were being hosted by as many as 12,000 communities. The movement's nadir, which occurred in the 1930s, has been blamed on the growing popularity of radio, movies, and automobiles. However, of late the Chautauqua has been experiencing a renaissance: More than 7,500 people travel to it each summer. The public lecture lives on.

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Perspective

The Early Years of Brain Imaging

In the early 20th century, neurosurgeon Walter Dandy developed the first techniques for in vivo observation of the central nervous system.

David M. Warmflash

At the turn of the 20th century, the newly discovered uses for x-ray technology in medicine and the emerging field of neurosurgery helped lead to the rise of a pivotal figure at Johns Hopkins School of Medicine, Walter Dandy. A protégé of the well-known neurosurgeon Harvey Cushing and later (after Dandy and Cushing had a falling out) of the well-regarded surgeon William Stewart Halsted, Dandy entered the field in 1910 after finishing medical school at Johns Hopkins at the age of 24. He would spend the rest of his career at the same institution.

Dandy completed general surgery training in 1918, with another neurosurgery pioneer, George J. Heuer, stepping in to guide him. Dandy's training in Halsted's general surgical service turned out to be a boon, because he was able to reapply innovations from other fields of surgery to neurosurgery. Under Halsted, he had already shown his promise by adapting an endoscope used in urology for looking inside the brain.

Dandy's various contributions included a plethora of techniques, such as aneurysm clipping, resection of cerebellopontine angle tumors, hemispherectomies, procedures for treating fluid buildup in the brain, and the first use of brain endoscopy. As Dandy worked on tragic cases of brain tumors and hydrocephaly—a dangerous accumulation of fluid in the brain—he realized that the system of canals where cerebral spinal fluid is produced and through which it flows, the *cerebral ventricular system*, could be used to view the brain in ways that would open up new treatments and could save some of his sickest patients' lives.

The Chesney Archives of Johns Hopkins Medicine, Nursing, and Public Health

Walter Dandy is one of the early influential figures in the field of neurosurgery. He began his training at Johns Hopkins School of Medicine in 1907 and spent his entire career there.

Dandy is particularly famous for his work advancing the understanding of the anatomy and physiology of the flow of cerebrospinal fluid. As a result of this exploration, his invention of the first brain imaging techniques, *air ventriculography* and then *pneumoencephalography*, became the gold standard for several decades. Dandy's early brain imaging techniques were invasive and risky, and they fell by the wayside in the 1970s once computed tomography (CT) scans and, later, magnetic resonance imaging (MRI) came on the scene. But this chapter in neurosurgery's history shows the incredible challenges that came with attempting to capture the earliest glimpses of the whole brain in a living person.

The Cerebral Ventricular System

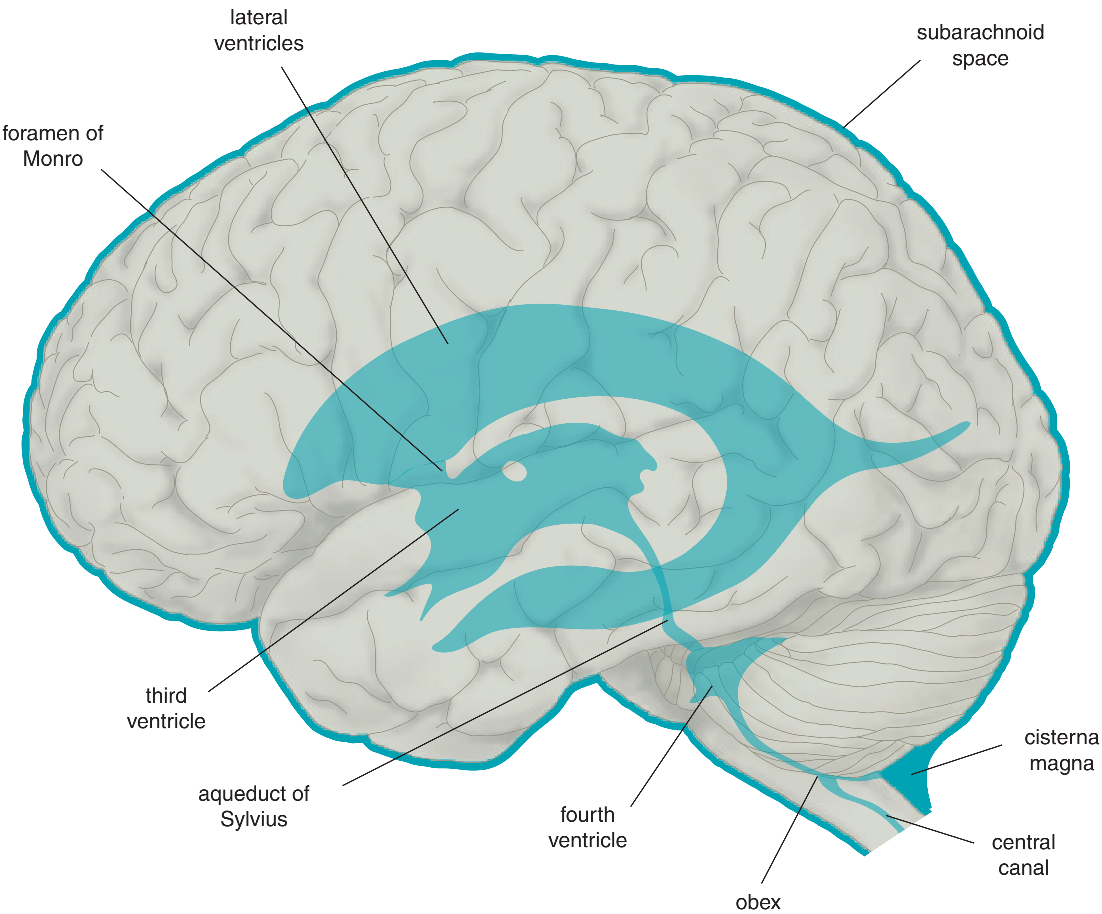
Dandy began his career at a time when the study of cerebrospinal fluid and disorders related to it were a focus in his field, with rapid advances. German surgeon Heinrich Quincke described the first lumbar puncture in 1891. In their studies of meningitis in 1903 and spinal tumors in 1907, respectively, physicians Georges Froin and Max Nonne described cerebrospinal fluid blockages and compression. In 1912, physician William Mestrezat made the first comprehensive study of the chemistry of cerebrospinal fluid. In 1914, Cushing provided

QUICK TAKE

Walter Dandy entered neurosurgery in the early 20th century, as the cerebral ventricular system and imaging with x-rays were major focuses in the field.

Dandy led multiple innovations that transformed his field, and many still influence today's practices. His brain imaging techniques were standard practice for several decades.

These invasive brain imaging techniques, now obsolete, show the tenacity, skill, and challenges involved as medical understanding of the central nervous system progressed.



Barbara Aulicino

evidence that cerebrospinal fluid was produced by special secretory tissue in each ventricle, called the *choroid plexus*.

Cushing also worked out how the ventricular system is connected, showing that the cerebrospinal fluid flows from the choroid plexus to the subarachnoid space and venous sinuses. On each side of the brain is a lateral ventricle, each of which connects through a channel called the *foramen of Monro* to the single, third ventricle (*see the figure above*). The third ventricle, in turn, connects through the *aqueduct of Sylvius* (also known as the *cerebral aqueduct*) to the fourth ventricle, which drains into the central canal of the spinal cord—which is why cerebrospinal fluid can be accessed through a lumbar puncture.

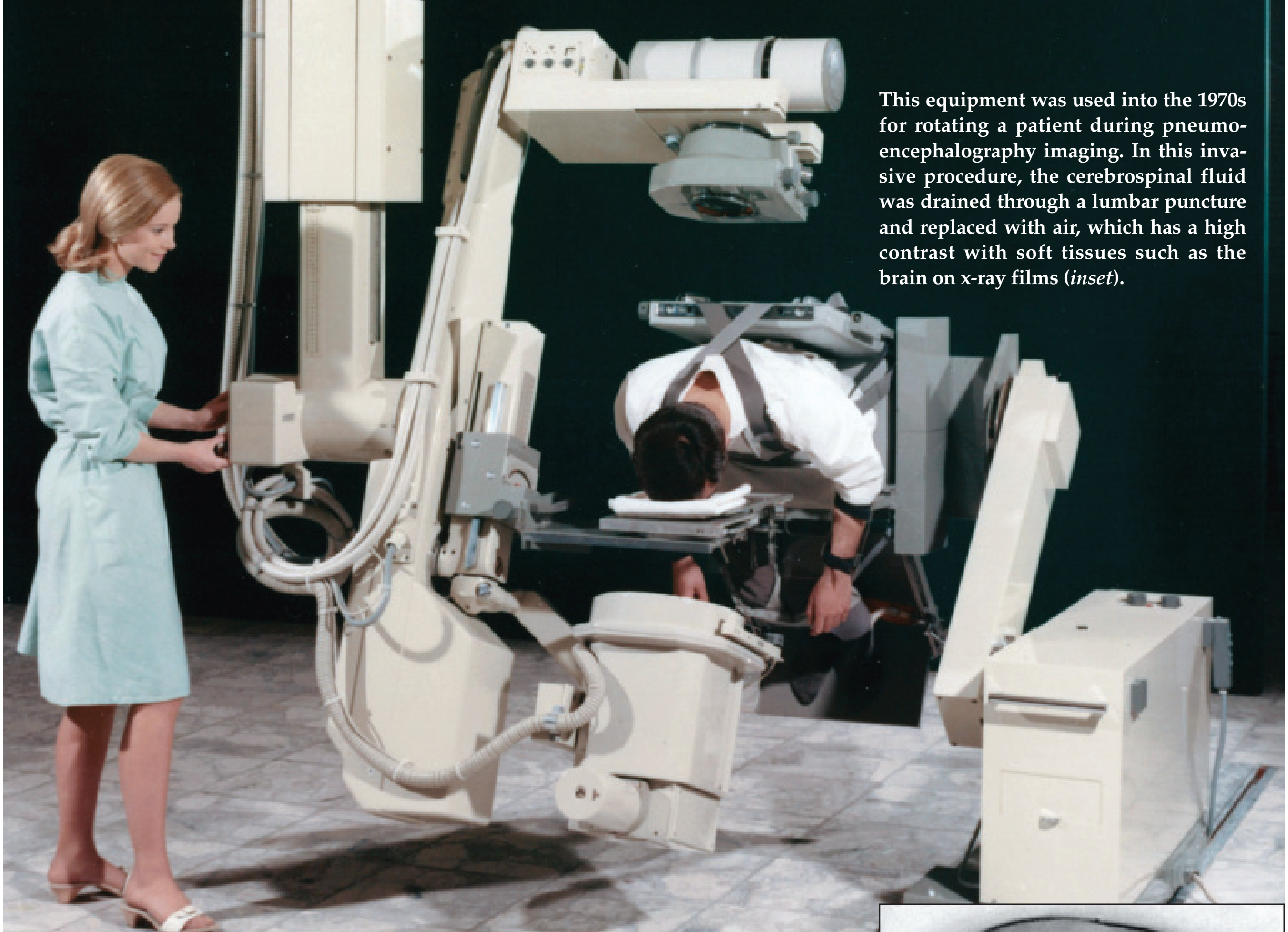
Dandy was training under Cushing at the time when the study of cerebrospinal fluid was the latter's focus, so the promising student became familiar with the ventricular system and diseases affecting cerebrospinal fluid. While working under pediatrician Kenneth Daniel Blackfan in 1913, Dandy and his mentor described the overproduction or obstruction of cerebrospinal fluid in this system in cases of hydrocephalus.

Mid-20th-Century Brain Imaging

Dandy's earliest work sought to understand cerebrospinal obstructions in the ventricular system in cases of hydrocephaly. Between 1914 and 1922, Dandy published 17 papers on hydrocephalus, a condition in which the cerebrospinal fluid does not drain properly, swelling the brain. At the time, this condition was often fatal. Dandy performed 381 surgeries on hydrocephaly patients between 1915 and 1946. Before Dandy developed techniques for imaging the brain, 50 percent of patients treated with surgery for hydrocephaly died, and those who did survive often died within a few months. Today, it's rare to lose a patient after an operation for hydrocephaly, and survival after five years is about 90 percent.

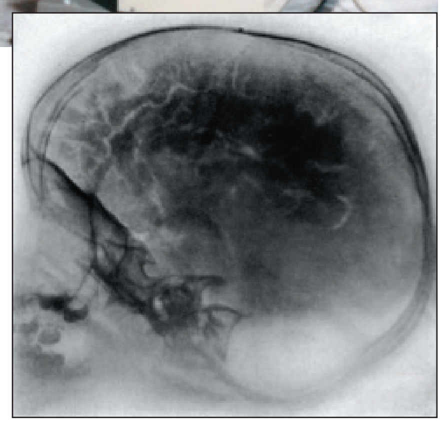
Though not so revealing of soft tissue, x-rays were extremely valuable for pulmonary imaging in the early 20th century, when pulmonary tuberculosis was widespread. While working on Halsted's general surgery service and looking at a chest x-ray, Dandy noticed a particularly radiolucent region on the film, under the patient's diaphragm, indicating the presence of air. The presence of air was not critical to the patient's case, so no one else was interested, but Dandy realized this meant that x-rays passed more easily through air than through tissues, and thus air could serve as a kind of negative contrast agent. Given that various liquids in use as positive contrast agents were toxic if circulated through the brain's ventricular system, Dandy decided to try using air instead. Accustomed already to accessing the brain's fluid-filled ventricular system through the skull with his endoscope technique, he reasoned that he could drain out the ventricles' normal fluid—cerebrospinal fluid—and replace it with air.

Dandy first tried replacing cerebrospinal fluid in the ventricles with air in 1916, while completing his fourth operation on a patient with hydrocephaly. Dandy drilled holes through the patient's skull as the route for sending air into the ventricular system—the *air ventriculography* technique. Dandy was interested both in tumors of the ventricles and in treating obstructive hydrocephalus. Both these issues can be treated most effectively when the tumors or blockage can be viewed and precisely located in the brain. Ventriculography allowed for earlier detection



This equipment was used into the 1970s for rotating a patient during pneumoencephalography imaging. In this invasive procedure, the cerebrospinal fluid was drained through a lumbar puncture and replaced with air, which has a high contrast with soft tissues such as the brain on x-ray films (*inset*).

Siemens Healthineers Historical Institute



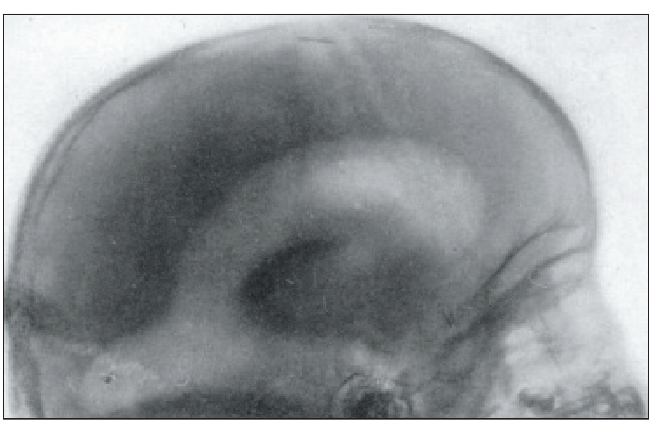
Ishaque et al., 2017

of hydrocephaly and better determination of where the blockage occurred. In a surviving ventriculogram from 1918 (*see image below*), an obstruction swelling the ventricle slightly in a three-year-old child with tuberculous meningitis is apparent, and the location of the obstruction causing hydrocephalus was identified. In this image, the foramen of Monro is even visible.

In 1919, Dandy started replacing cerebrospinal fluid with air via a lumbar puncture instead of through cranial burr holes. Taking x-rays of the brain after the lumbar air replacement technique and after moving the patient around in different ways, Dandy discovered that he could image the entire brain (*see photo above and x-ray inset*). This breakthrough is where the term *pneumoencephalography* comes into play. The technique worked because the injected air could be spread throughout the subarachnoid space, which is beneath the deepest layer of the meninges that surround the brain, and which bends around with all the brain's curves and twists. Pneumoencephalography, which was later depicted in the 1973 horror film *The Exorcist*, required the patient to be flipped upside down and through different positions to enable gravity to get the air throughout the subarachnoid space. To do so, patients had to be sedated.

Prior to Dandy's work, the combination of neurological examination and poor-quality x-rays could provide neurosurgeons with the locations of only approximately one-third of intracranial tumors. Dandy's air-based innovations made it possible to see almost all of them.

Air ventriculography and pneumoencephalography were dangerous, with potentially fatal outcomes. Mortality among patients receiving pneumoencephalography could be as high as 30 percent. At minimum, these procedures caused bad headaches, nausea, and vomiting. The decision to undertake these surgeries was serious. And although Dandy did not participate in such studies, some doctors used pneumoencephalography in disturbing and highly unethical ways: to study patients with schizophrenia, children with autism, or, in the case of Rudolf Lemke of the University of Jena in the 1940s, homosexual men. It's no wonder that medicine was quick to abandon both techniques as soon as CT scanning came on the scene in the 1970s.



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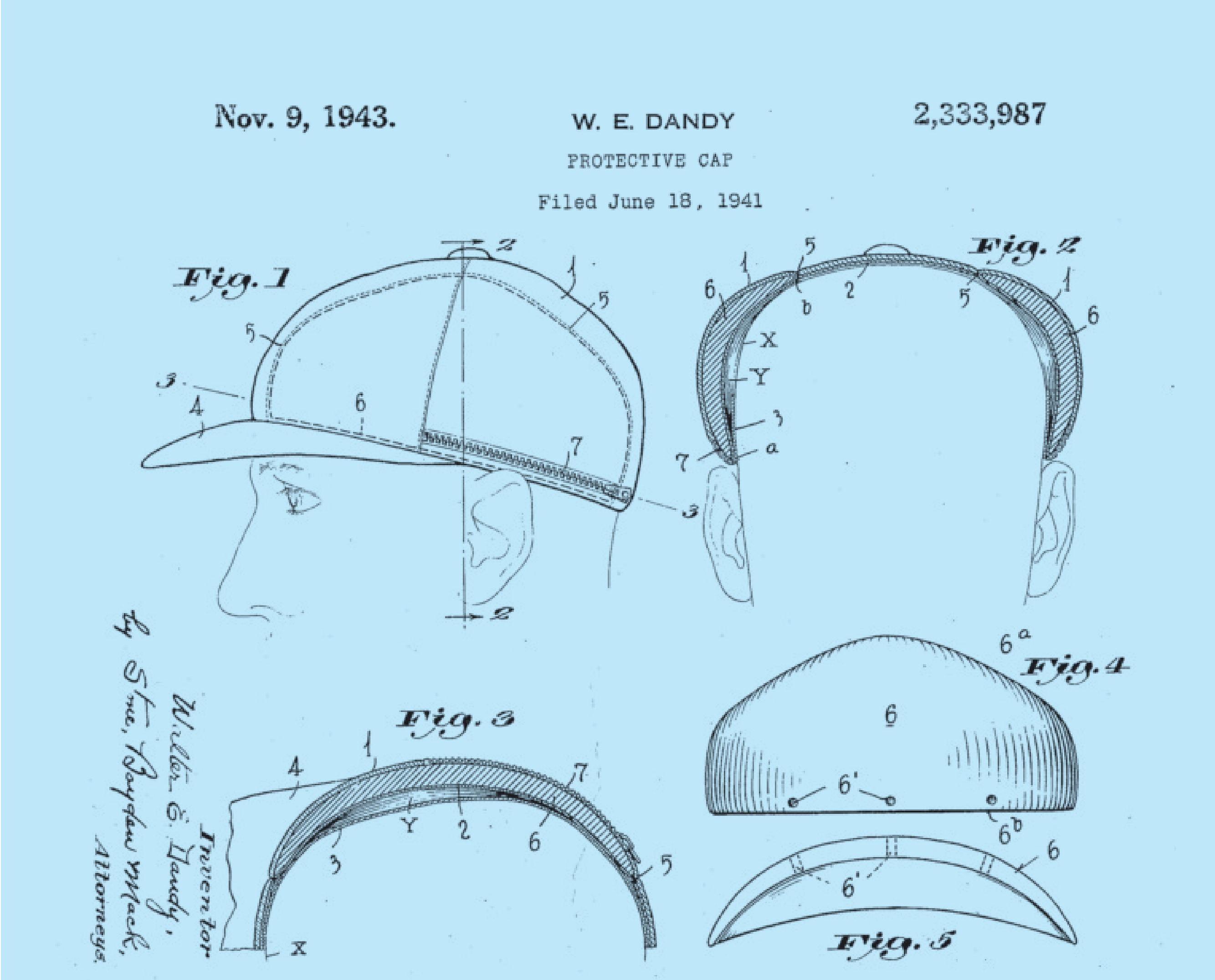

United States Patent and Trademark Office

Inventing the Batting Helmet

With all of Dandy's fundamental contributions to neurosurgery, he also managed to apply his expertise to another realm of health care: sports medicine. While batting on June 1, 1940, protected only by a canvas baseball cap, Brooklyn Dodgers' star 21-year-old shortstop, Pee Wee Reese, collapsed when struck in the head with a fastball. He returned to play several days later, allegedly with no major neurological damage, but other batters of his era commonly suffered traumatic brain injuries. From the late 19th century and into the mid-20th, brain injury was the most common reason for baseball-related death. Consequently, Reese's and one of his teammate's injuries triggered an effort by the Dodgers' team management to develop batting helmets, a project that soon came to involve Dandy, an avid baseball fan as well as a recreational player.

Back in medical school, Dandy had captained the school's baseball team. Then, in 1912, one of his first major surgical cases involved a cranial cyst that had developed after the patient had been struck in the head by a baseball. Dandy's professional and personal interests both reinforced the need for better head protection in the sport. Subsequent to the summer of 1940, Dandy's idea for an armored cap developed, inspired by horse jockeys' helmets, with plastic padding on either side of the head. Major League Baseball introduced this protective helmet in 1941, just in time to protect another Dodgers rookie, Pete Reiser. When he was struck in the head in April 1941, his doctor called him "very lucky" to have a minor concussion rather than a fractured skull, thanks to Dandy's helmet. Other teams soon followed the Dodgers' lead.

This protective cap became standard headgear until 1952, when a new fiberglass and plastic resin helmet that provided full head coverage, securely fitted with leather padding, came on the scene. Clearly, Dandy's efforts left an impressive legacy in multiple fields, from sports medicine to modern neurosurgery practice.

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David M. Warmflash is a medical researcher, astrobiologist, author, and freelance science communicator. Twitter: @CosmicEvolution

A Chemist's Guide to 3D-Printed Cuisine

Amateurs and entrepreneurs are producing uniquely shaped foods, from confections to meat alternatives to astronaut meals.

Matthew R. Hartings

In 2011, graduate students Kyle and Liz von Hasseln were using an old Z310 gypsum 3D printer to create architectural models in their home in Los Angeles. Then inspiration struck: They realized the same 3D-printing technology could be applied to food, and could be used to build confections with structures that had never been possible before. The von Hasselns eventually developed and patented a method for printing complex edible objects. In 2012, they founded the Sugar Lab and began to partner with prominent chefs all over the world. Sugar Lab is a boutique startup that is just beginning to investigate the vast and wild possibilities of 3D-printed foods. Many others are exploring this area as well: high-end chefs, companies trying to replace meat and fish with printed alternatives, and—perhaps most excitingly—a vast community of home DIY types who are taking food where it has never gone before.

Access to printers (through public libraries, makerspaces, or purchase for as low as $100) has substantially lowered the barrier to entry into this world. Additionally, online communities such as Thingiverse, Cults, MyMiniFactory, and many more provide open-access resources for printable files and printing best practices that give valuable guidance for novices. Thingiverse alone now hosts more than two million files.

I am a chemist who designs new materials for 3D printing. In my research, I have printed objects that can remove environmental pollutants or that can store hydrogen gas for fuel cells, among other applications. I am also a food chemist. Although I have never developed my own processes for printing food, I have printed foodstuffs, such as peanut butter and Nutella, as part of my research. For me, Nutella is a benchmark, of sorts. It has just the right consistency (thickness and squeezability) to match some of the specialty materials I am developing. As a parent who needs to feed Nutella-hungry teenagers, I am partial to the argument that this hazelnut treat is not cheap. But in my lab, where research and development are time-consuming, the ingredients I use bust the budget in comparison. Printing Nutella is a way to make sure that when I print for my experiments, everything will come out just right. My goals are practical, but I have to admit that printing food is also simply fun.

There is something quintessentially sci-fi and futuristic about a machine that can prepare any number of dishes with the push of a button. For home amateurs, 3D-printed foods offer a creative outlet and an opportunity for play. For chefs, 3D printers are a tool for crafting food in totally new ways. In the long run, 3D printing has the potential to create foods that are more sustainable, less cruel, and more creative for all of us.

How to 3D Print Foods

For any type of 3D printing, edible or otherwise, the style of printing dictates the kinds of materials that can be used, and what can be made from them. The most recognizable style of 3D printing is based on *extrusion*. People who played with Play-Doh as children will remember the press that would squish out different shapes of Play-Doh pasta. That's what 3D printers do, too.

The pasta company Barilla has taken that childhood joy and used it as the inspiration for a 3D printer that can make all sorts of new pasta shapes. Their printing venture, BluRhapsody, has a number of inventive pastas in different sizes and shapes that are available for purchase. What intrigues me most about these pastas, along with how they look on a plate, is their ability to hold and conceal sauces until the diner cuts them open. In the culinary world, individual styles of pasta are known to be compatible with specific kinds of sauces. For example, heavy cream-based sauces and meat ragus pair better with thicker noodles such as tagliatelle, while thinner sauces with even consistency pair better with spaghetti or angel hair. With their new 3D-printed pasta shapes, Barilla can help chefs innovate in their pasta and sauce combinations.

What 3D printing can accomplish that regular pasta making can't is performing complicated patterns of extrusion. During extrusion, some material

QUICK TAKE

Access to 3D printers has expanded over the past 10 years, and with it, innovations in 3D-printed foods and the capacity to play with this tech in one's home kitchen or makerspace.

Methods for 3D printing food involve extruding a liquid material that can hold its shape after its placement on a platform, or "gluing" together food particles into a particular shape.

Some chefs and entrepreneurs are exploring new possibilities for shapes, flavors, and applications, including elaborate confections, meat alternatives, and food for astronauts.

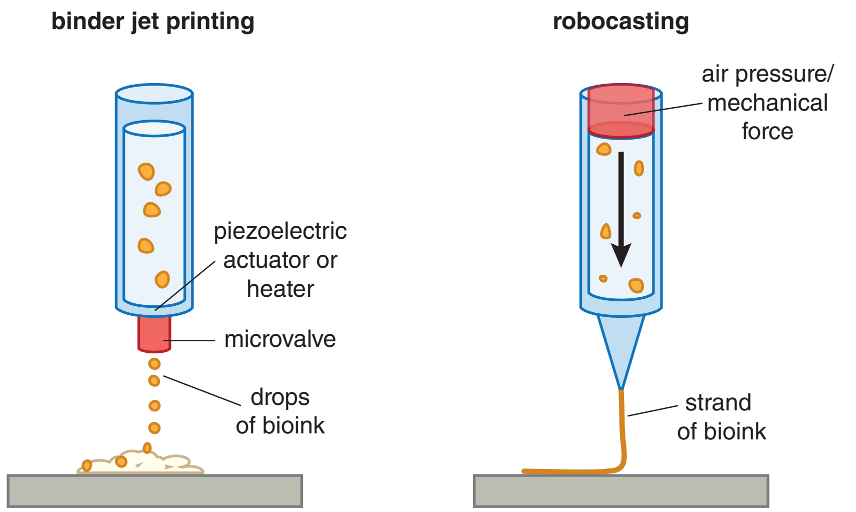
Sugar Lab/Current 3D

The food company Sugar Lab offers sugar "cubes" with far more faces and complexity than your standard cube. These confections add pizzazz to coffee, tea, or cocktails, and may also be flavored. The sugar sculptures are put together using a method called *binder jet printing*, in which a powder such as sugar is mixed with a binding agent, which is fed through a printhead not unlike that of an inkjet printer.

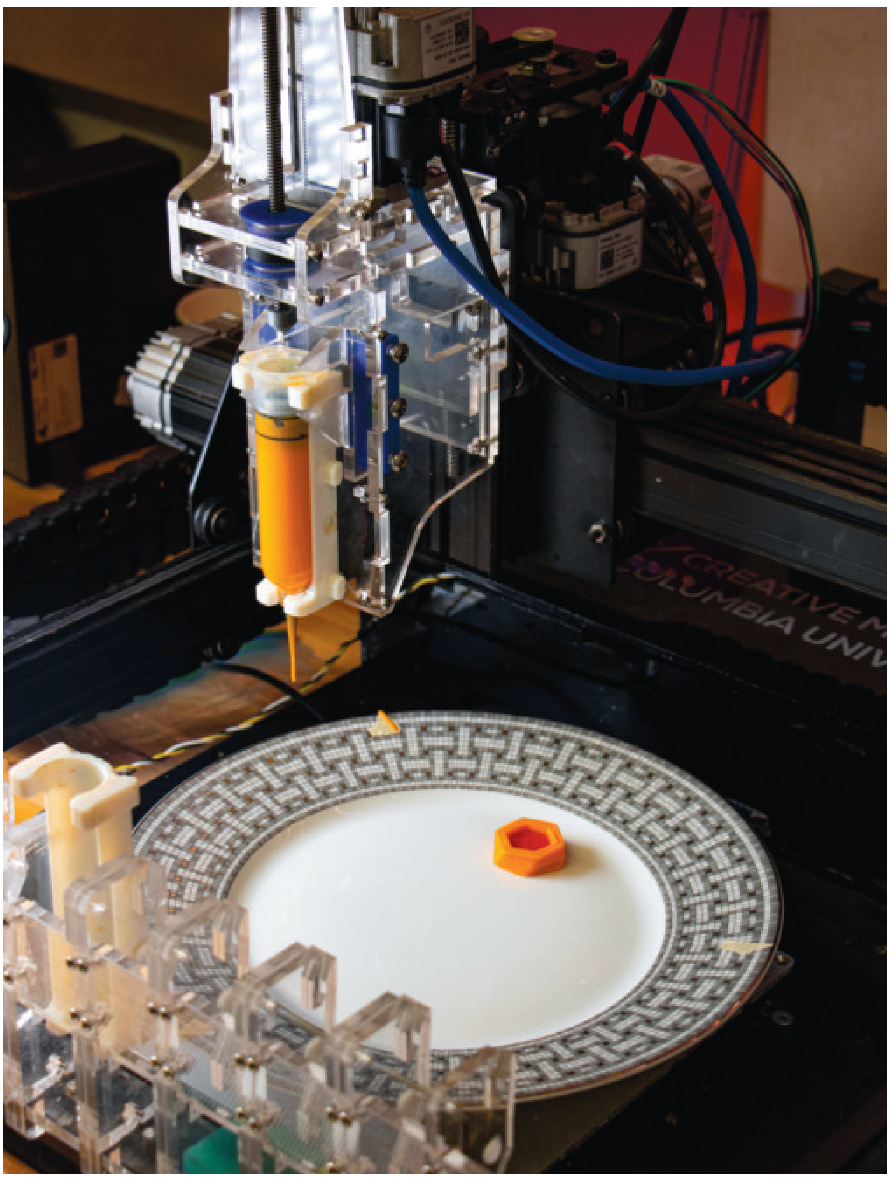
is pushed through a small nozzle and deposited on a platform. The nozzle moves horizontally around the platform, depositing material as instructed by a computer program until the object fully takes shape.

The prototypical extrusion printer uses a spool of plastic that is passed through a heated nozzle during a print. These are *fused deposition modeling* (FDM) printers. Needless to say, typical 3D-printing plastics—such as acrylonitrile butadiene styrene and polylactic acid—are not very tasty or healthy. The extrusion-based printers used in 3D food production are similar to FDM printers; however, instead of using a spool of plastic, they typically print using liquid that is held in a syringe. Printers that work in this way are termed *direct ink writing*, *bioprinting*, or *robocasting*.

The most important material property for robocasting is that the extruded material, or *ink*, needs to hold its shape after it is placed on the platform where the structure is being printed. In my lab, for example, Nutella is one of the inks that I print. There are a number of ways to design a printable



The two primary ways to 3D print food involve either "gluing" together powdered foods into a particular shape using a binding agent such as food-grade wax or syrup (*left*), or extruding a liquid through a syringe-like printhead (*right*). The latter method requires that the liquid holds its shape after extrusion, either through cooling or by using chemical fixing agents.



ink. One system involves keeping the liquid in a heated syringe and printing onto a cooled or room-temperature platform where it will solidify rapidly. Printing chocolate or liquids that contain gelatin or agar is done this way; they are liquid while in the warmed syringe and immediately set when extruded onto the cooler platform.

A second way to achieve a 3D shape is to use a chemical fixing agent to set the printed liquid into a solid. An example of this method involves printing a viscous, water-based ink of sodium alginate into a container of water with calcium ions. The calcium ions are able to set the alginate into a solid. People who have played around with techniques from molecular gastronomy at home will immediately recognize these as the same ingredients used to make fruit caviar. The groundbreaking chef Ferran Adrià developed the technique for making fruit caviar (colorful spheres of fruit juice encased in a Jell-O-like shell) using the same ingredients, and intrepid 3D printing enthusiasts have co-opted Adrià's innovation for their own uses.

Another common approach to designing a printable ink involves a *thixotrophic liquid*, which eliminates the need both for cooling and for chemical fixing agents. *Thixotrophic* is just a fancy word for a material that flows like a liquid when pressure is applied but doesn't flow when there is an absence of pressure. This property may seem strange, but it is one we rely on almost daily. Ketchup and toothpaste (and Nutella and peanut butter, too) are all examples of thixotrophic materials. To get a good feel for this method of 3D printing, imagine a tube of toothpaste. If you remove the cap and turn the tube so that the open end is facing the floor, nothing happens. It is only when you squeeze the tube that any toothpaste comes out. Additionally, when you put toothpaste on your toothbrush, it holds its shape indefinitely. This is precisely the type of property that is targeted for robocasting thixotrophic inks.

Three-dimensional printers are being adapted to work with edible ingredients to create custom foods, such as this sculpture printed out of carrot puree. For this kind of robocasting, one needs to develop an ink that flows when pressure is applied to it, but that keeps its shape once printed. Chefs aspiring to this kind of printing can thicken liquids with food-safe hydrocolloids.

When cyclodextrin, a specialty chemical made from corn, is mixed with an oily ingredient, such as chili oil or hazelnut spread, the result is a powder. This chemistry is useful for binder jet printing.

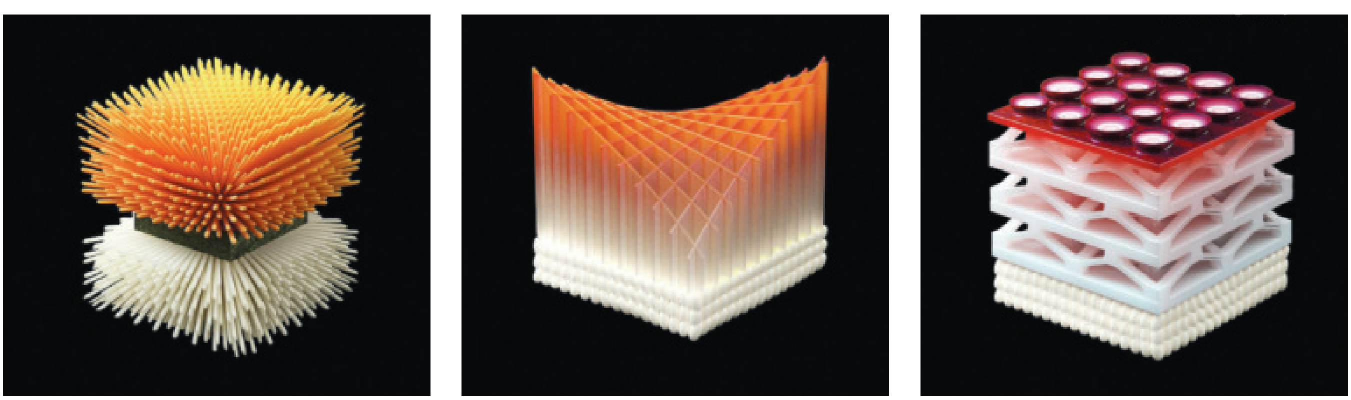
Robocasting is a wonderful technique for exploring and experimenting with different 3D-printing materials. The only requirement is that the user must select appropriate flow properties for their ink. There are a number of commercial food-safe hydrocolloids available to help optimize these inks. Martin Lersch, a professional chemist and expert in modernist cuisine, has organized a recipe collection called *Texture* on his blog, Khymos, that highlights a number of hydrocolloid-thickened liquids. *Texture* is a great place to start for those who want to make their own robocasting inks. Although Lersch doesn't refer to them as inks, he lists several recipes that will produce printable inks. If you're curious, give the olive oil soba noodles a try! The methyl cellulose used in this recipe is a material I use in my research lab in designing printable inks, to give them just the right consistency for printing.

Perhaps the biggest impediment to robocasting printing for culinary purposes is the availability of suitable printers. You can purchase food- or chocolate-specific printers, but they are costly, typically more than $1,000. I would suggest one of two options here. First, there are several cheaper, commercially available ceramic/clay printers that can also print food-based inks. Second, one could convert a FDM printer into a direct-ink-writing printer through some fairly straightforward modifications. I have recently made these modifications to one of the printers in my own lab following directions put together by materials scientist Adam Feinberg and his coworkers at Carnegie Mellon University. One of the great things about 3D printing is the availability of open-source hardware and software, which enables people to get exactly what they want out of their experience.

In addition to robocasting, there is a whole other technique for printing edible objects, called *binder jet printing*. Binder jet printing (also known as *powder bed and inkjet printing*) is based on a process in which particles of a powder (such as cornstarch or sugar) are glued together. Sugar Lab, for example, uses binder jet printing to make candies and other decorative, edible pieces. In these printers, there is a reservoir for the powder and a build container where the powder comes together with the binding agent. Finally, there

In late 2022, the U.S. Food and Drug Administration approved the first lab-grown meat for human consumption.

Sushi Singularity is a planned high-end restaurant to be based in Tokyo, and they are developing a variety of 3D-printed innovations in Japanese cuisine. Among their menu items are powdered sintered uni (*left*), which mixes sea urchin powder and rice flour to create a melt-in-the-mouth experience; anisotropic stiffness steamed shrimp (*middle*), which simulates the texture of shrimp; and negative stiffness honeycomb octopus (*right*), which has a bouncy texture like that of octopus.



Reuters/Amir Cohen/Alamy Stock Photo

Vegan meat substitutes are a big focus in the world of marketable 3D-printed foods. The plant-based meats shown here mimic beef and are produced by the startup Redefine Meat. The 3D-printing process can create the varied textures that characterize meat. At present, the company's products are available only in select restaurants.

is a printhead (like in an office inkjet printer) that contains the binding agent to hold the powder together. At the beginning of the print, the reservoir is full and the build container is empty. The print starts when the bottom of the reservoir is raised and some of the powder is pushed into the build container.

Aleph Farms/Technion–Israel Institute of Technology

The world's first slaughter-free rib eye steak, made by 3D printing lab-grown beef components, has been produced by Aleph Farms and the faculty of biomedical engineering at the Technion–Israel Institute of Technology. This and similar products are slowly making their way to market, pending approval from the U.S. Food and Drug Administration.

The inkjet printhead deposits "glue," such as food-grade wax or sugar syrup, at precise locations on the surface of the build container to selectively cohere some particles. At this point, the build surface is lowered, the reservoir surface is raised, the process starts over, and these steps repeat until a full object has been glued together.

The user has several options for tailoring materials with binder jet printing. The first step is deciding which powder to use. For food printing, fabricators most commonly use sugar-based powders. Many other pantry ingredients are already available in powdered form as well, although most of these are not pleasant to eat on their own. An adventurous user could make their own, ready-to-eat powder blends with combinations of sugar, cornstarch, chocolate, and other flavorings. Another option is to use cyclodextrin, a specialty chemical derived from corn (N-Zorbit is a commercially available cyclodextrin) that can be mixed with an oily ingredient to make it the right consistency, resulting in ingredients such as powdered butter or powdered Nutella.

The other important decision in binder jet printing is which type of glue to use. In practice, most of the interesting creative choices come up at this juncture. The process here is

analogous to the way an office color-jet printer uses a set of ink cartridges to produce color images on printed paper. A binder jet food printer can use multiple color cartridges as well, each containing food-grade dye, to create an elaborately artistic food print. A major difference between the office printer and the binder jet printer is that the binder jet cartridges also need to contain a glue to hold the particles together. That glue can come in several forms, depending on the powder used.

BluRhapsody

This elaborately shaped pasta dish, made by the Barilla-owned company BluRhapsody, was inspired by Greek pottery, and here is filled with caprino cheese and fava beans and served on purple cabbage. Robocasting allows chefs to get creative with pasta shapes.

Realistic Food Mimics

Although 3D printing enables the creation of a wide variety of elaborate forms, one of the most popular applications of 3D food printing is mimicry of familiar foods. Often, business ventures that 3D print foods have focused on making vegan or lab-grown mimics of animal-based foods. Investors have put billions of dollars into start-ups in this space, and the price of producing cell-cultured meat has dropped from a burger costing $330,000 in 2013 to about $9.80 in 2022.

Plant-based foods have the potential to remove many of the negative aspects of animal-based diets. Reduced land, water, and energy use, reduced greenhouse gas emissions, and increased nutritional value are commonly cited justifications, although none of these goals can be met with current efforts in plant-based meat alternatives. There are two main ways to produce animal-free meats. The first is to use all vegan ingredients, which is how the Impossible Burger is produced. The second is to use lab-grown meat products. These cultured meats are nearly identical to the muscles that develop in animals, with the crucial difference that they are grown from cells in a laboratory. In late 2022, the U.S. Food and Drug Administration approved the first lab-grown meat for human consumption: chicken meat produced by Upside Foods. Although both of these manufacturing methods can generate foods with meatlike flavor, matching the texture of a chicken breast, steak, or roast is a challenge that only 3D printing can meet.

The value of the 3D printer is that it can assemble ingredients in a form that resembles the structure of real meat—which veggie burgers and even Impossible Burgers do not do. Whether using plant-based meat substitutes or lab-grown meats, the race is on to bring 3D-printed steaks to market. Two companies, Redefine Meat (plant-based) and Steakholder Foods (lab-grown) are aiming to hit the market first. The problem is that replicating a steak poses a number of specific difficulties that must be overcome.

There are many different properties that make a steak a steak. First and foremost is composition. A steak isn't a homogeneous material. It is primarily muscle interspersed with a marbling of fat. Both the fat and the muscle have different culinary properties, and 3D printing can facilitate a realistic arrangement of "muscle" and "fat." The cooked texture is important here, too. Looking specifically at the muscle portions highlights these challenges. We have a number of different expectations

Natural Machines

This hummus castle, printed by 3D-printer company Natural Machines, is an example of an elaborate build using robocasting.

NASA

Foodies, experimental chefs, and commercial start-ups are taking food where it has never been before—including 3D bioprinters in space. Developing better food for astronauts using 3D printers is an active area of research. Here, a team from the start-up Made In Space tests a 3D printer in the Microgravity Science Glovebox Engineering Unit at Marshall Space Flight Center.

The great thing about 3D printing foods is that most possible foods in this space haven't been made yet.

for our cooked steaks: Rare, medium, and well-done are all points along gradients of steak "doneness" that are dictated by structural changes of the proteins actin and myosin.

Steaks can also be characterized as having distinct fibers. These are most recognizable when eating roast beef, but steaks display a fibrous nature, too. Additionally, a steak must be able to undergo the *Maillard reaction*—the chemical changes that occur during searing that bring a crispiness to the exterior of the steak along with the darkened color and enhanced flavor. A 3D-printed steak must also have the right color, taste, and aroma to be appealing.

So far, Steakholder's beef morsels are a 3D-printed meat that is getting close to reaching the commercial market. Redefine Meat's products are available only in select restaurants for the time being; it will take time to scale up production to the point where these products will be available in supermarkets.

So how have Redefine and Steakholder done so far? Tim Anderson, a London-based chef, recently wrote for 3Dprint.com that the texture of the newest iteration of 3D-printed steaks is a "triumph," but that the appearance, juiciness, and flavor leave much to be desired.

Other pushes for the 3D printing of realistic food mimics have come from the military and from the field of space exploration. In both these arenas, long deployments go hand in hand with a lack of fresh food because of spoilage and storage issues. If nutritious and appetizing food mimics could be produced from shelf-stable packets of 3D-printing inks, the quality of life for soldiers and astronauts would be increased. One NASA-supported project developed a 3D printer that can make a pizza, even spawning a company, BeeHex, to commercialize the technology. More recently, NASA started a Deep Space Food Challenge that is funding research into devices that can fabricate familiar foods (including a proposed food replicator from BeeHex) for long-duration space missions. This example is another product in development that is not quite ready for prime time. As with 3D-printed steaks, these companies seem to be slowly working their way toward the commercial market.

Creativity Unbound

For everyone from home foodies to experimental chefs to commercial start-ups, the primary appeal of 3D printing foods is that it allows culinary creations that are unlike anything that has existed before. For now, most of the action is taking place at the maker-space or boutique level, because the tech is still so new and unexplored.

Sushi Singularity is a high-end Japanese restaurant planned in Tokyo that has embraced the flavors and textures of sushi while also exploring novel structures. Their 3D-printed food experiments include cell-cultured tuna in a filigreed cube, and octopus sculpted in a honeycomb lattice with negative stiffness (*see figure on page 101*). Most of their printing appears to be extrusion-based, using components that undergo computer-controlled mixing to generate the right flavors and textures. They also use a powder-based printing technique that incorporates high-powered lasers to fuse powders together.

At Sugar Lab, the von Hasselns and their team keep tinkering with powder and glue recipes to explore new food geometries. They have 3D printed cocktail garnishes in the shape of cut diamonds that add bitters and sweetness to a drink. They are also exploring complex geometries, from icosahedron truffles to bouillon "cubes" in the shape of emblems for the members of the K-pop band BTS.

The first commercial experiments in 3D-printed food products are necessarily exotic and expensive, because they are early forays into the huge potential for printing foodstuffs; 3D printing is an enabling technology through which people can turn their imaginations into reality. As a scientist and food lover, I am intrigued by what people have accomplished so far. I really want to try a 3D-printed steak! Even though they don't yet live up to their standard-bearers, it's only a matter of time before the flavor and appearance come around. I am also excited to see what completely *new* types of foods (that aren't trying to be something else) will emerge from this market. In either case, I hope that people recognize that change typically happens more slowly than we anticipate. It will take a while to print the perfect steak or pizza. It will take a while to experiment with formulations to get flavor and appearance just so. And it will take a while for regulatory agencies to grant approval, and for us to then see adoption on the market.

However, I think the results will be worth the wait as we see where boundaries are pushed. I am expecting to do my own experimentation in pushing those boundaries. Maybe that means printing a version of Willy Wonka's Three-Course Dinner Gum using controlled-release polymers. Or it could mean figuring out how to replicate the properties of complex pastries. The great thing about 3D printing foods is that most possible foods in this space haven't been made yet. There's lots of room to play. I hope to see many of you on this journey.

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Matthew R. Hartings is an associate professor of chemistry at American University in Washington, DC. His research interests include food, mineral formation, and 3D printing. He is also the author of Chemistry in Your Kitchen *(Royal Society of Chemistry, 2017). Twitter: @sciencegeist; email: hartings@american.edu*

"The trick to efficient packing is helical scaffolding with loops. And an iron."

The Inevitably Incomplete Story of Human Evolution

With an unknown amount of evidence yet to be found and possible bias in our interpretations, current accounts of human evolution can only be provisional.

Bernard Wood and Alexis Uluutku

People often enjoy reading about where humans come from and how we developed into the unusual creatures we are today: upright-walking, omnivorous mammals who inhabit every continent (and who enjoy reading about our own evolution). Such accounts generally offer a presentation of the fossil evidence for human evolution and a narrative describing how we gradually transformed from our apelike ancestors, via a series of intermediate forms, into modern humans. Popular narratives on this topic generally include explanations about how, when, and why our human ancestors' posture became upright, their gait became bipedal, their diet shifted from vegetarian to a combination of meat and plants, and their brains enlarged.

Unfortunately, we have to disappoint you. Although a narrative of this type would look like an accurate account of human evolution, it would almost certainly differ from the real evolutionary history. Instead, this article will lay out our reasons for thinking the existing human fossil record is incomplete in almost all respects, with little chance that any narrative explanation offered today can be the right one. If the human evolutionary story were a play or a novel, many of its characters would be absent, misrepresented, or poorly developed, and the plot would have many holes.

Indeed, we do not yet have all the evidence needed to generate an accurate narrative of human evolution. Why then do paleoanthropologists routinely present our current understanding as if it were authoritative? We suggest that it is a profoundly human trait to want a straightforward and complete story. We have all grown up with oral and written narratives, just as our ancestors did for tens, maybe even hundreds, of thousands of years, and nearly all these stories follow a full narrative arc. We know who the main characters were, we know how the story started out, and we know how it ended. We expect the story of our evolution to follow the same arc.

A straightforward account is elusive, however, because of two factors that inevitably complicate any attempt to reconstruct evolutionary history: what is missing from the fossil and archeological record, and the great variety of ways to interpret that record.

The missing evidence is of course an unknown quantity. We know we do not have all the fossil and archaeological evidence we would like, but we don't know how much evidence remains to be found. Whether we are now missing as much evidence as we already have, twice as much, or half as much, is an open question. The second factor—how valid one or another interpretation of the record may be—presents its own challenges. In the rest of this article, we will look more closely into each of these factors to explore why sound scientific hypotheses about our origins are so hard to come by.

Working Assumptions

For a long time, most of the evidence that was available—whether from outward appearance, diet, or geographic range—seemed to indicate that chimpanzees, bonobos, and gorillas were more closely related to one another than to modern humans. Recent research at the genomic level, however, has changed this consensus. There is now abundant evidence that the living animals most closely related to modern humans are chimpanzees and bonobos, with gorillas as a slightly more distant relative. Molecular differences between modern humans, on one hand, and chimpanzees and bonobos, on the other, suggest these two lineages—hominins and panins—diverged at

Reconstructions by paleoartist John Gurche allow fossils to be seen as the living creatures they once were. Clockwise from top right: *Homo heidelbergensis* (estimated to have existed 700,000 to 200,000 years ago); *Homo floresiensis* (95,000 to 60,000 years ago); *Australopithecus afarensis* (2.9 to 2.1 million years ago); *Paranthropus boisei* (2.3 to 1 million years ago); *Australopithecus africanus* (3.3 to 2.1 million years ago); *Homo erectus* (1.8 million to 100,000 years ago); *Homo neanderthalensis* (250,000 to 27,000 years ago).

QUICK TAKE

The evidence for human evolution—including fossils, artifacts, and ancient genetic material—constitutes a record that is compelling but incomplete.

Paleoanthropologists cannot assume the current body of evidence represents the complete assemblage of ancestral human species or the full range of variation within each species.

The scientific understanding of human origins must be open to continual change in order to take account of new evidence as it becomes available.

John Gurche

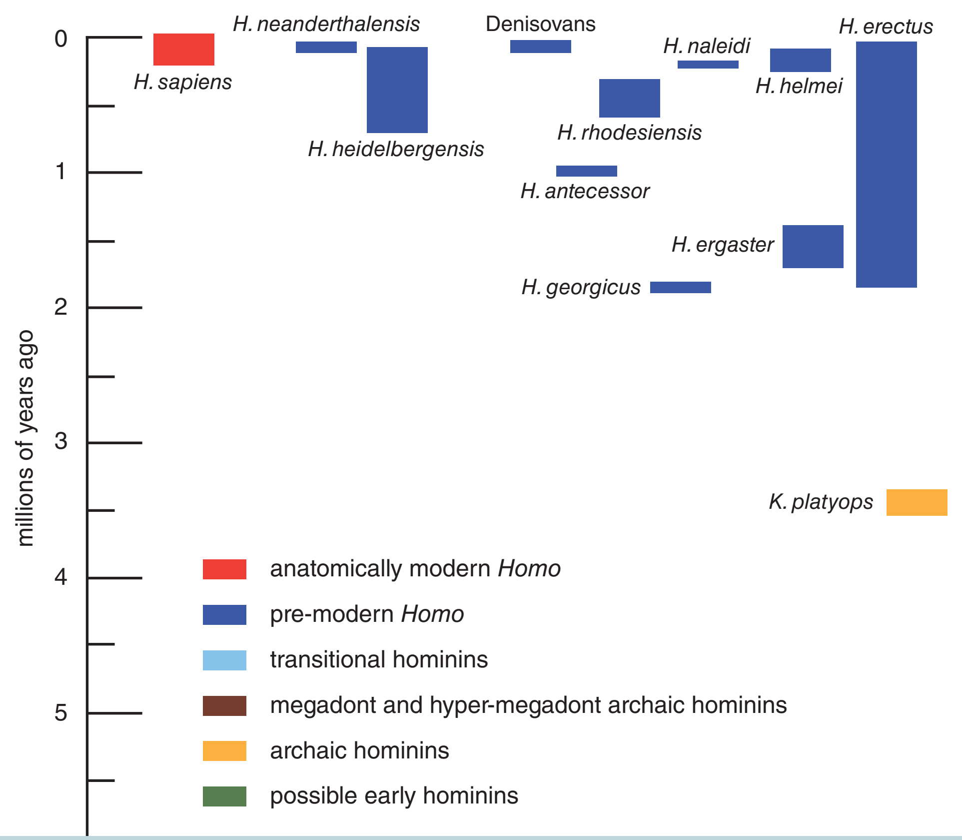
least five million years ago, and probably closer to eight million. The earliest humans clearly differed from us in many large and small ways, with modern humans like ourselves appearing only about 300,000 years ago.

Given the contemporary geographic range of chimpanzees and bonobos and the evidence from the fossil record, the most recent common ancestor of hominins and apes almost certainly lived in Africa. For the purposes of this review, let's assume that the hominin lineage (a line consisting only of humans and our direct ancestors and close relatives) goes back about eight million years, and also that modern humans first emerged in Africa, as Charles Darwin hypothesized in 1871 in his book *The Descent of Man*. From these two premises it follows that somewhere in the African fossil record between about eight million years ago and the present day, there should be evidence of at least one hominin species, and probably more than one. If the human evolutionary lineage is anything like that of most other forms of life, it resembles a loosely braided rope rather than a single continuous strand.

Reconstructing that braided rope would be a scientific challenge in any case, but it is all the more difficult because of major gaps in the fossil record. Consider a scenario in which researchers have access to a complete fossil record of hominin evolutionary history. In this paleoanthropological daydream, each hominin species that ever existed would be represented in the fossil record. The evidence for each species would appear in the fossil record soon after it originated and would disappear just before it became extinct; moreover, each species would be represented by fossils from the entire geographic range of its habitat.

In reality, of course, the hominin fossil record that is currently available to researchers falls far short of this theoretical scenario. Only a small proportion of the individuals in any terrestrial mammalian species retain their physical integrity long enough to begin the process of fossilization. It takes many slow physical and chemical changes to transform a newly deceased animal into one or more fossilized fragments, and of these fragments only a small subset are eventually recovered and identified. Even if we were able someday to recover all of the hominin fossils that have been preserved anywhere on Earth—paleontologists call this the *potential fossil record*—the record we have at present is almost certainly many orders of magnitude less complete. Hence, the fossil evidence with which we are working is far less informative about diversity of species, geographical range, and temporal span than either the potential fossil record or the scenario set out in our thought experiment. In other words [*spoiler alert*], hominins exemplify the aphorism "absence of evidence is not evidence of absence.'"

Hominin taxa and site samples according to a



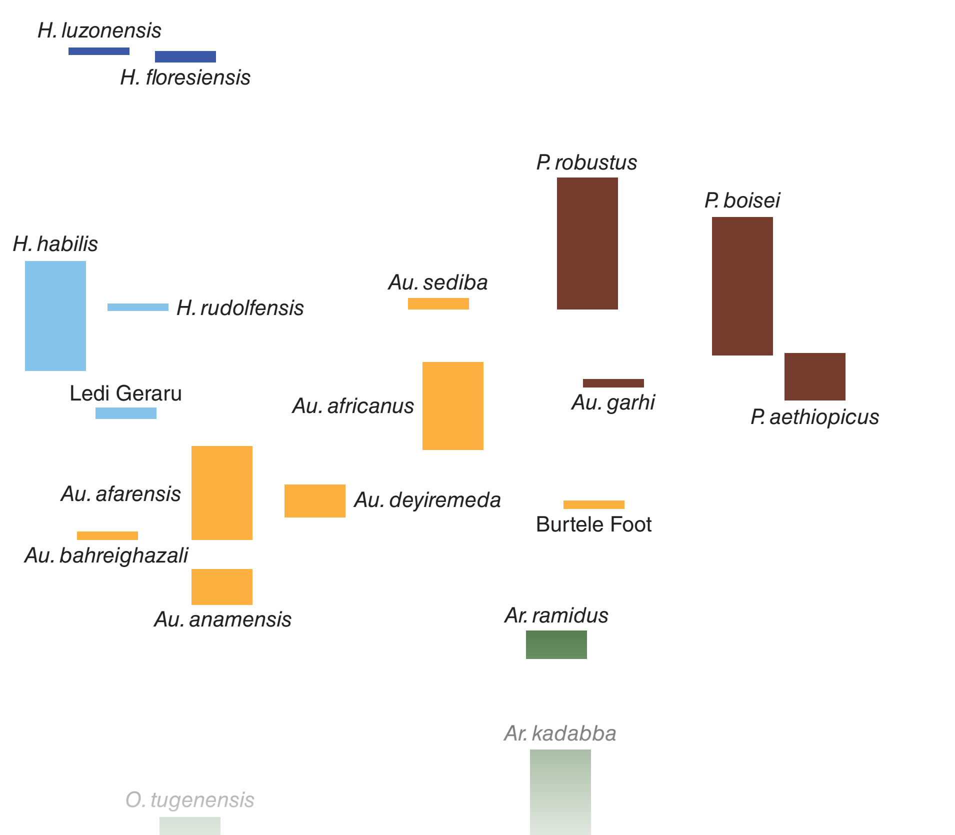
Researchers disagree considerably as to how many species are represented in the fossil record of human evolution; the disagreement rests mainly on the question of how much variation the samples of a given species may exhibit among themselves, while still being considered one species.

Proponents of one school of thought maintain that considerable variation may exist within a species; those who think this way are known informally as "lumpers." By

How Many Taxa?

The large but unknowable difference between the number of hominin species that actually existed, and the number of species researchers think are represented in the fossil record, leaves plenty of room for error. It is all too easy to overestimate the *taxic diversity*, or number of species, for example by overlooking the possibility that the fossils found in Africa up to now may be too small a collection to capture the full range of variation within a species. Occasionally, as shown in the figure on page 110, one new fossil is so different from the fossil evidence of a contemporary species that the case for taxonomic distinctiveness is obvious, but few claims for new hominin taxa are as securely based as this example. Even if a hominin species is well sampled from several sites, those samples are unlikely to capture the full range of variation of the parent population from which the samples are drawn. For this reason, if a new site yields fossils that differ only slightly in size and shape from previously known

"splitters" taxonomy



contrast, in the "splitters" taxonomy shown here, most of the variations are interpreted as dividing marks between species rather than assortment within a species. Each column stands for a purported species (except in rare cases like the Burtele foot, where the identity of the species remains in question). The bottom and top of each column reflect the latest information about, respectively, the dates of the first and last appearances of that species in the fossil record.

samples, it does not necessarily mean the new fossils belong to a new species. Until we have larger samples for fossil hominin species, the procedure traditionally used in paleoanthropology to identify new species—that is, asking whether a new sample lies outside the range of variation of the existing site samples—is likely to lead to the overreporting of new taxa.

It is equally easy to underestimate the number of early hominin taxa, especially those that may have lived in Africa, simply because we may not yet have discovered evidence of them. Contrary to its appearance in most commercial atlases (owing to the Mercator projection and other such representations), Africa is a very large continent—more than three times larger than the continental United States.

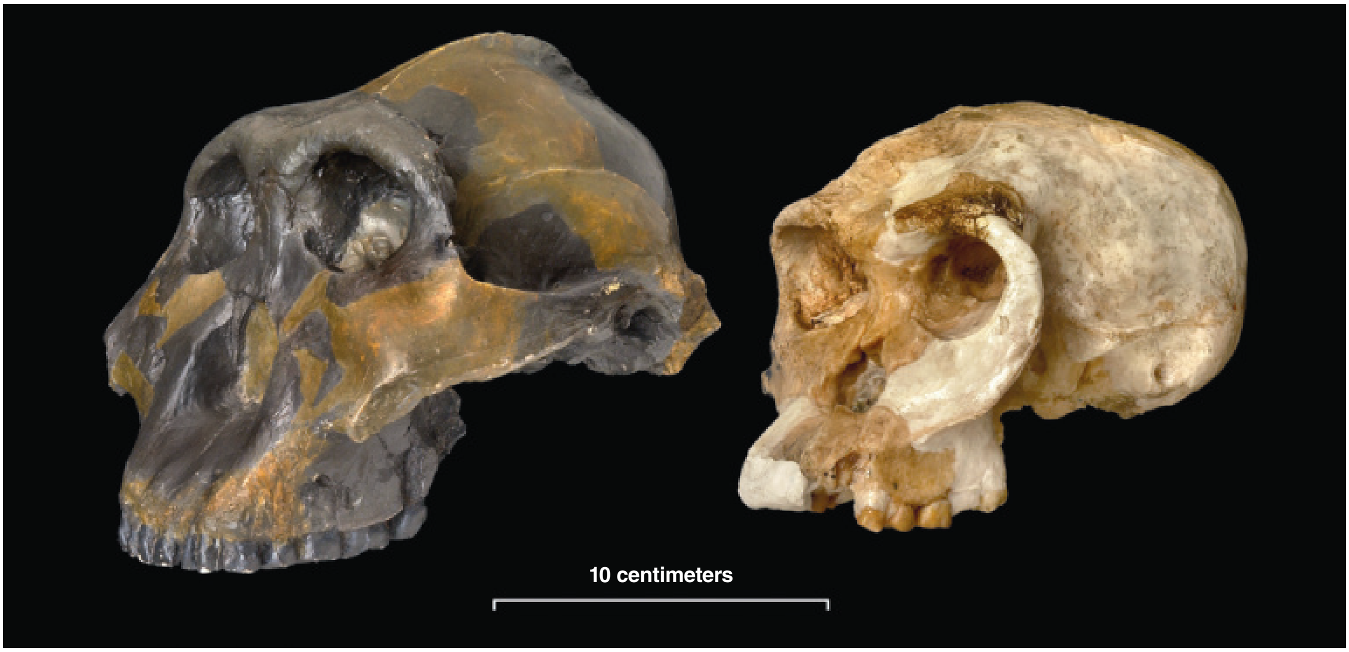
Hypotheses involving extinct taxa inevitably rest on evidence from the bones and teeth that are preserved in the fossil record. Unfortunately, the hard tissues of some types of living monkeys and apes can look so similar that it is almost impossible to tell which bone or tooth comes from which species. By contrast, the visual, auditory, and olfactory signals that individuals use to recognize potential mates are all based in soft tissues that leave no trace in the fossil record. Such signals were probably based in early hominins' soft tissues as well. We must rely on bones and teeth to tell how many extinct species of hominins there are—a circumstance that is more likely to cause researchers to underestimate taxic diversity than to overestimate it.

In all of Africa's 30 million square kilometers, just two regions provide the vast majority of the fossil evidence for human evolution. One is the region of the Eastern African Rift System, where sedimentary rocks are exposed by erosion; many fossils have been found here at sites that were once lakeshores or riverbanks, where hominin fossils accumulated naturally. In the second region, the high veldt of southern Africa, hominin fossils have come to light among the sediments that accumulated in caves in dolomitic limestone. Most of these were hominin bones that fell or were washed into the caves along with soil and the bones and teeth of nonhominins; in several remarkable cases, the skeletons are so complete that they suggest individual hominins perished after being trapped in the caves.

Even if we add in a small number of sites in other parts of the continent, a generous estimate of the total hominin-fossil-bearing area of Africa amounts to only one or two percent of the habitable land surface. To assume that hominins lived for millions of years in just a few tiny portions of the continent—in the very same areas where fossil-bearing sediments have happened to come to light millions of years later—flies in the face of common sense. We must allow for the strong possibility that there were more hominin species within Africa as a whole than have yet been found.

In the interval between the origination of a species and the time it goes extinct, the likelihood of its leaving a fossil record depends on several factors. Some of the interval may have been characterized not by sedimentation but by erosion, which would have interfered with the development of any fossils. Even if sedimentation took place, the surface area of sediments that later became exposed and available for fossil-collecting is likely to vary. Paleontologists understand that what they call *rock availability* is an arbitrary but important element in a taxon's chance of leaving a fossil record from the time span of its existence. No exposed sediments, no fossil discoveries.

One more factor to weigh in is the *collection effort*, or the amount of time spent looking for fossils at any given spot. Researchers who have studied these two factors recently concluded that rock availability and collection effort likely have a profound influence on whether a taxon left an accessible fossil record.



The Natural History Museum/Alamy Stock Photo

Fossils that are many hundreds of thousands of years old can sometimes be too damaged or fragmented to conjure up a specific image, but sometimes they show sharp contrasts that make it easy to distinguish between species. The fossils shown here, for example, although they both lived in the area of Olduvai Gorge about 1.8 million years ago, clearly represent two different species, *Paranthropus boisei* (*left*) and *Homo habilis* (*right*).

Population Data

Empirical evidence suggests that at many—if not most—sites where hominins are found, they are rare components of the mammalian fossil record. This relative scarcity may well indicate that early hominins were rare mammals in the past, but it is not conclusive. Obtaining reliable information about the incidence of hominins in site samples is no simple matter.

If the human evolutionary lineage is anything like that of most other forms of life, it resembles a loosely braided rope rather than a single continuous strand.

For one thing, it is important to recognize that all fossil samples are skewed in one way or another. Although it was formerly assumed that the bones found at a fossil site were a small but essentially unbiased sample of the animals living at that place millions of years earlier, this view no longer holds. Some general biases are well known: Small mammals tend to be systematically underrepresented and large ones overrepresented. In addition, the habitat preference of a species affects whether its members are likely to become part of the fossil record. When mammals go to water holes to drink or to the lakeshore to graze, they are vulnerable to predators, and in both locations their bones are likely to be preserved and subsequently fossilized in the sediments that are deposited by rivers, streams, or rising lake levels. Conversely, mammals that live in more arid habitats are likely to be underrepresented in the fossil record. Without having the complete paleoecological history of a specific site, we cannot know whether the biases there were working in favor of, or against, the chances of hominins being preserved.

A second complication in determining the relative abundance of hominins at a given site is the collection strategy used by researchers. Most research teams collect all the mammal fossils that can be identified, but some teams focus on only a few mammal groups such as primates and carnivores. (It is worthwhile to remember, too, that for the reasons discussed earlier, all research groups are likely to overestimate the relative abundance of hominins as a percentage of the mammalian fauna.) The collection strategy least likely to exaggerate the frequency of hominins on the landscape is one whereby all fossil mammals are collected, as was the case, for example, at Omo-Shungura, in Ethiopia—and even here, hominins are estimated to have made up less than 1 percent of all large mammals.

Taken together, these considerations suggest that relatively small samples of fossil mammals are unlikely to show evidence of hominins at a particular site, even if hominins were living on that landscape at the time. The bottom line is that an enormous number of fossils belonging to common mammals, such as pigs and antelopes, would have to be recovered from a given site before we could infer anything from the absence of hominin fossils. Here again is an illustration that the absence of evidence is not evidence of absence.

In our thought experiment outlining the ideal fossil record, one important feature was that evidence of a species

would appear soon after the species took shape and would disappear just before its extinction. The earliest fossil *evidence* of a species is not equivalent to the species' earliest *existence*, because new species most often originate in small numbers in marginal habitats, which means they will likely become visible in the fossil record only after they have existed for some considerable time. And if, as is likely, a species' extinction is preceded by a reduction in population size, the species will likely disappear from the fossil record well before its actual demise.

It's possible to estimate the discrepancy between the origination of a species and when it first appears in the fossil record, or between its last appearance in the fossil record and its extinction, but many of the methods currently used have a high error rate or apply only to one or two specific sites. Researchers are now exploring the use of various models to estimate such discrepancies across the whole species range.

Stone Age Institute

A striking sight along the highway in Ngorongoro Conservation Area, Tanzania, is a monument to two illustrious discoveries in human evolution, *Paranthropus boisei* (*left*) and *Homo habilis* (*right*). Designed and sponsored by the Stone Age Institute (affiliated with Indiana University), the monument calls attention to the nearby site of Olduvai Gorge and its associated museum. Sculptor Festo Kijo (*far right in this photo*) based the larger-than-life renderings on fossils that had been excavated from Olduvai Gorge by Mary and Jonathan Leakey.

Biases in Interpretation

With a few well-publicized exceptions, such as the Piltdown fraud, we can be sure the fossil and archeological records we use to reconstruct human evolutionary history are reliable. The fossils are real, they come from where researchers say they come from, and their ages are based on sound and well-established methods. The techniques we use to reconstruct the posture, locomotion, and diet of early hominins sometimes lack precision and are always subject to improvement, but the results can be replicated. What is less reliable are interpretations of all that evidence, particularly when it comes to species recognition. This point is crucial because the bedrock of any attempt to reconstruct human evolutionary history is taxonomy, which means working out how many species are represented in the fossil record. If researchers don't get that right, then all the downstream inferences based on those decisions could go awry.

In questions about the number of species represented by the existing fossil record, several different factors might influence a researcher's interpretation. There is no standardized way of judging whether a newly discovered sample of fossils justifies the recognition of a new species, and therefore the process is open to the vagaries of different forms of cognitive bias. One of the most insidious of these is confirmation bias: the all-too-human tendency to see what we expect (or hope) to see, sometimes at the cost of seeing accurately.

Rarely operating at a conscious level, confirmation bias involves focusing on and giving excessive weight to evidence that supports an already-favored conclusion while overlooking or devaluing evidence to the contrary. Probably the best known example of confirmation bias in this field centers on a fossil that eventually proved to be no more than a hoax, the notorious Piltdown Man. (*See box on page 112.*) One of the dangers of confirmation bias is that it can lead individuals, including researchers, to reach conclusions prematurely, stopping the search for objective evidence because they perceive the case for an outcome (such as the recognition of a new species) to be stronger than it actually is. The result can be to prop up incorrect hypotheses or to promote overconfidence in a hypothesis for which there is some valid, but not yet conclusive, evidence. There exist effective ways to counteract these tendencies—for example, by rigorously challenging the preferred hypothesis or by shifting from advocacy to an objective weighing of the evidence pro and con—but these are easier said than done.

The bedrock of any attempt to reconstruct human evolutionary history is taxonomy, which means working out how many species are represented in the fossil record.

How different does a new fossil have to be from specimens in the existing fossil record before a researcher can reasonably assume it represents a new species? After all, any observed differences might be attributed to a fossil's state of preservation (whether that involves deformation, an increase in size owing to matrix-filled cracks, or a decrease in size caused by erosion), ontogeny (comparing a young individual with an old one), sex (comparing a male with a female), regional variation, and so on. Only when all these possibilities have been ruled out can researchers determine the degree of morphological variation they are prepared to tolerate within a species. In practical terms, paleontologists usually use the extent of size and shape variation within closely related living species as their criteria. These criteria come with an important caveat, however, because living species display variation at what is effectively an instant in geological time, whereas fossil taxa are usually sampled across geological time.

The smaller the sample, the greater the opportunity for the observed value of a trait to be biased by random sampling and measurement error.

Obviously, at each stage in the complicated process just described, researchers can legitimately make judgments that lead to different conclusions about how many species should be recognized. For example, what we consider to be *Homo erectus* encompasses a morphological variation greater than any known extant ape. It is not unreasonable, therefore, that some paleoanthropologists favor the splitting of this taxon into more than one species based on time and location. When biological anthropologists disagree about classification, it is often difficult to tell whether the differences arise from the way each one interprets a particular part of the primate fossil record or from different perspectives about what constitutes a species.

Both kinds of disagreement usually play a part. Researchers holding a gradualistic view of evolution generally stress the importance of continuities in the fossil record. Those who think along these lines tend to opt for fewer species and are known informally as *lumpers*. Their counterparts, who conceive of evolution more in terms of a punctuated equilibrium, emphasize the importance of discontinuities within the fossil record and therefore tend to end up with more species in their hypotheses; this group has the informal name of *splitters*. (For the example mentioned in the previous paragraph, a lumper would include every variation of *Homo erectus* into one species, regardless of time or location, whereas a splitter would define different variants of *Homo erectus* as two or even three species.) The bottom line is that taxonomic proposals, phylogenetic reconstructions, and classifications are all hypotheses. They are all subject to testing and will inevitably be corroborated or revised as new evidence accumulates and as more effective analytical methods are developed. Such is the nature of science.

The small sample sizes that are common in the study of early hominin fossils can leave researchers open to other kinds of bias as well. It is common to overestimate the stability (and therefore the replicability) of a small sample and to underestimate the role

Wikimedia Commons

Paleoanthropology is subject to confirmation bias, whereby researchers may give undue weight to evidence that confirms their preexisting ideas. Such was the case with Piltdown Man, a fossil assemblage excavated in 1912 near the village of Piltdown, England. With its distinctively human-shaped skull and massive, apelike jaw, Piltdown Man appeared to embody the long-sought Missing Link, bridging the evolutionary gap between apes and humans. The investigating scientists (shown here in a 1915 painting by John Cooke) may have also been influenced unconsciously by the location of this discovery in England, their homeland.

In 1949, new tests revealed the age of the skull to be much younger than originally supposed, and further study proved the specimen to be a hoax: A human cranium had been combined with the jaw of an orangutan, the teeth filed, and the bones stained to match the color of the surrounding gravel. Piltdown Man was eventually determined to be the work of amateur archaeologist Charles Dawson, who appears in the above painting (*standing to the right of Darwin's portrait*). Dawson's motive remains a mystery, but his legacy is assured as the source of one of the great cautionary tales in science.

of random sampling variation, attributing differences between samples to explainable effects. The result can be to produce exaggerated confidence about the extent to which the patterns seen in small samples are reliable indicators of the parent population. The smaller the sample, the greater the opportunity for the observed value of a trait to be biased by random sampling and measurement error.

When these factors, in turn, are combined with an open-ended search for traits that are different from other samples and with the use of open-ended criteria for defining "different," researchers may fall into the trap of generating sample-specific idiosyncratic results that cannot be reproduced by others. This type of result demonstrates what has been called the Texas sharpshooter bias: Instead of testing the accuracy and precision of their shooting using a predetermined target and agreed-upon rules, inept marksmen fire blindly at the side of a barn and then draw a target around the largest accumulation of random bullet holes.

Pascal Goetgheluck/Science Source

A rich source for fossils of early *Homo sapiens*, or anatomically modern humans, has been the site of Qafzeh Cave, near Nazareth, Israel, where the remains of at least 15 individuals have been discovered. Near the skeleton shown here were signs of deliberate burial, such as ochre-stained tools and pieces of ochre. With an estimated age of 90,000 to 100,000 years, Qafzeh may offer one of the oldest records of ritual carried out by human ancestors.

Sharing What We Know

When we weigh the existing fossil record and the existing methods for its interpretation, it is evident that in both areas we don't yet have what we need to put together a comprehensive narrative of human evolutionary history. Accounts based on incomplete data sets can sometimes, misleadingly, sound definitive. When new evidence later emerges and the narrative of human evolution is revised to accommodate it, the public can be forgiven for thinking that paleoanthropologists might not always know what they are doing. Worse, creationists often seize on such revisions as evidence that paleoanthropologists have *no* idea what they are doing.

Both reactions arise from a misunderstanding about how we make progress in paleontology, the historical science that attempts to reconstruct evolutionary history, and particularly in paleoanthropology, the branch of paleontology that focuses on reconstructing human evolutionary history. It is true there are aspects of paleoanthropology, such as the number of extinct hominins known from sites in Western Europe, that have changed very little for several decades. At the same time, there have been dramatic changes in other, less-well-explored regions of the world, as well as in other scientific areas. Some of these changes have been completely unexpected, such as the discovery of *Homo floresiensis*, a dwarfed early hominin from the island of Flores, and of the Denisovans, a likely new species recognized on the basis of DNA evidence before there was any obvious traditional fossil evidence for it. By contrast, feats such as extracting ancient DNA from hominins that lived almost half a million years ago represent years of painstaking work. None of these discoveries have invalidated previous narratives; rather, they have added to their complexity. Far from showing the failure of the paleoanthropological enterprise, they speak to its health and vitality.

It is accepted practice in paleoanthropology to present detailed reconstructions of human evolutionary history that rarely acknowledge the extent to which they are incomplete and bound to change. But this practice does a disservice to all concerned. It would be more helpful, as well as more accurate, to acknowledge that the hominin fossil record is incomplete and that there are therefore limits to what can be said about it. By all means, let's use the fossil record to generate narratives, but not without stipulating that those narratives are only explanatory devices, not comprehensive descriptions of past events. Overselling narratives based on incomplete data runs the risk of feeding mistrust between scientists and the public. There is still much we have yet to learn about both the human evolutionary story and the best ways to tell it.

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Bernard Wood is a professor of human origins at George Washington University. A medically trained paleoanthropologist, he is the author of 19 books that range from a monograph on the hominin cranial remains from Koobi Fora to the popular Human Evolution: A Very Short Introduction *(Oxford University Press, 2019). His research focuses on hominin systematics and phylogeny reconstruction. Alexis Uluutku is a PhD candidate in the Center for the Advanced Study of Human Paleobiology at George Washington University. She uses ecological theory along with 3D geometric morphometrics to test interactions between early* Homo *and* Paranthropus boisei *in eastern Africa during the Pleistocene. Email for Wood: bernardawood@gmail.com*

Unearthly Beauty

The outer reaches of the Solar System offer glimpses of reality outside our human experience.

COSMIC ART

If the role of art is to extend our senses and our experiences into the realm of the unknown and the unfamiliar, to imbue us with a sense of awe and wonder at the glory and grandeur of nature, and to push the boundaries of what we know and feel, then deep space exploration has provided some of the most spectacular and humbling kinds of art that humans have ever produced.

The images included here are from the farthest reaches of our Solar System, where humans have never traveled: Uranus, Neptune, and Pluto. Although the photos were taken by uncrewed space probes, robots did not produce the art; people did. Robotic missions and instruments are built by and operated by virtual explorers back here on Earth, who get to plan and compose the photos, choose the timing and the framing, set the exposures, and digitally process the images afterward. These images celebrate the scientists and engineers who push human civilization—including the ways in which we produce and experience art—beyond the physical limits of our planet.

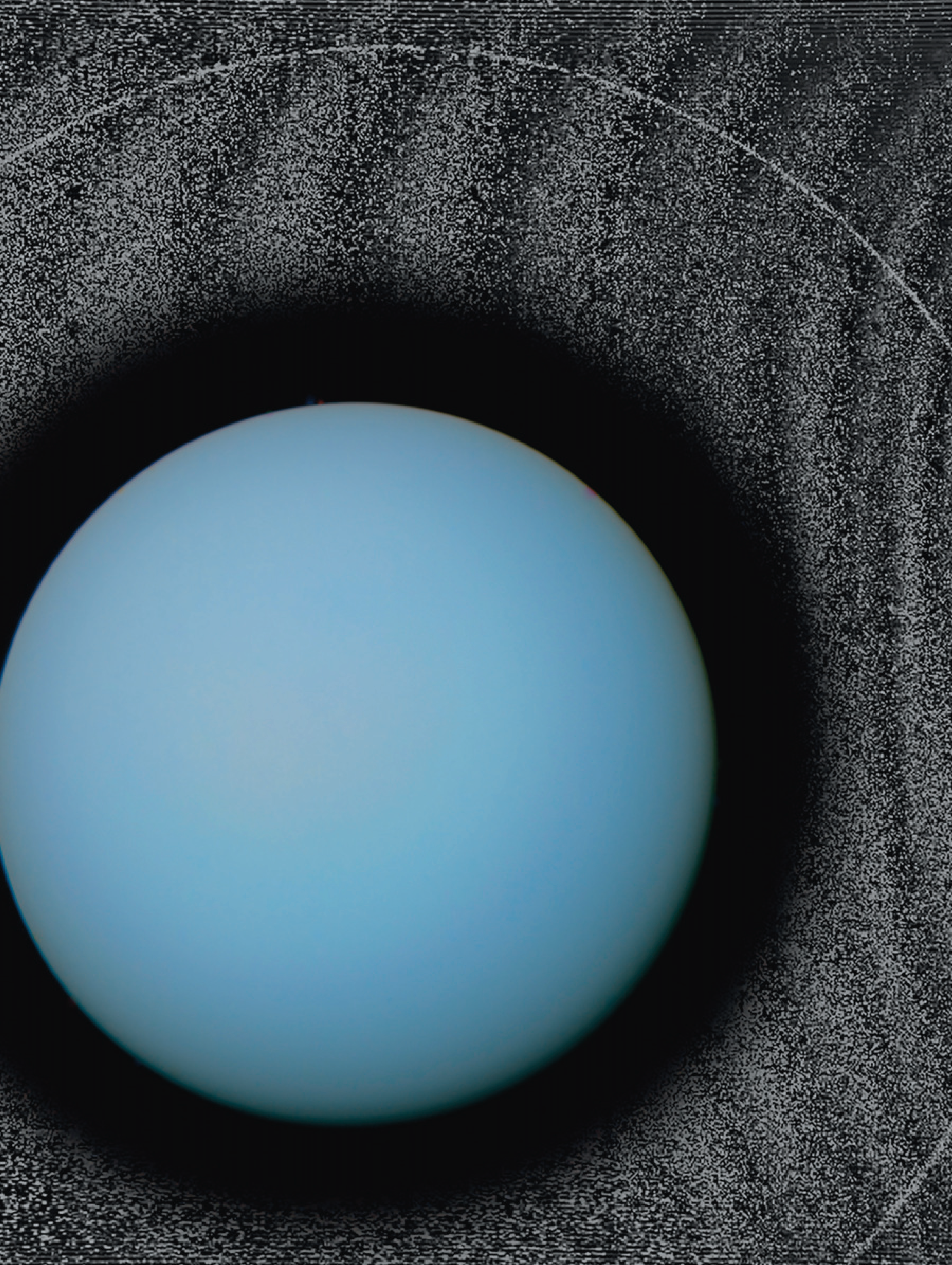
Jim Bell is a professor in the School of Earth and Space Exploration at Arizona State University and a distinguished visiting scientist at NASA's Jet Propulsion Laboratory. He was president of the Planetary Society from 2008 to 2020 and received the 2011 Carl Sagan Medal from the American Astronomical Society. Excerpted and adapted with permission from The Art of the Cosmos *by Jim Bell (2022, Union Square & Co.). Email: jim.bell@asu.edu*

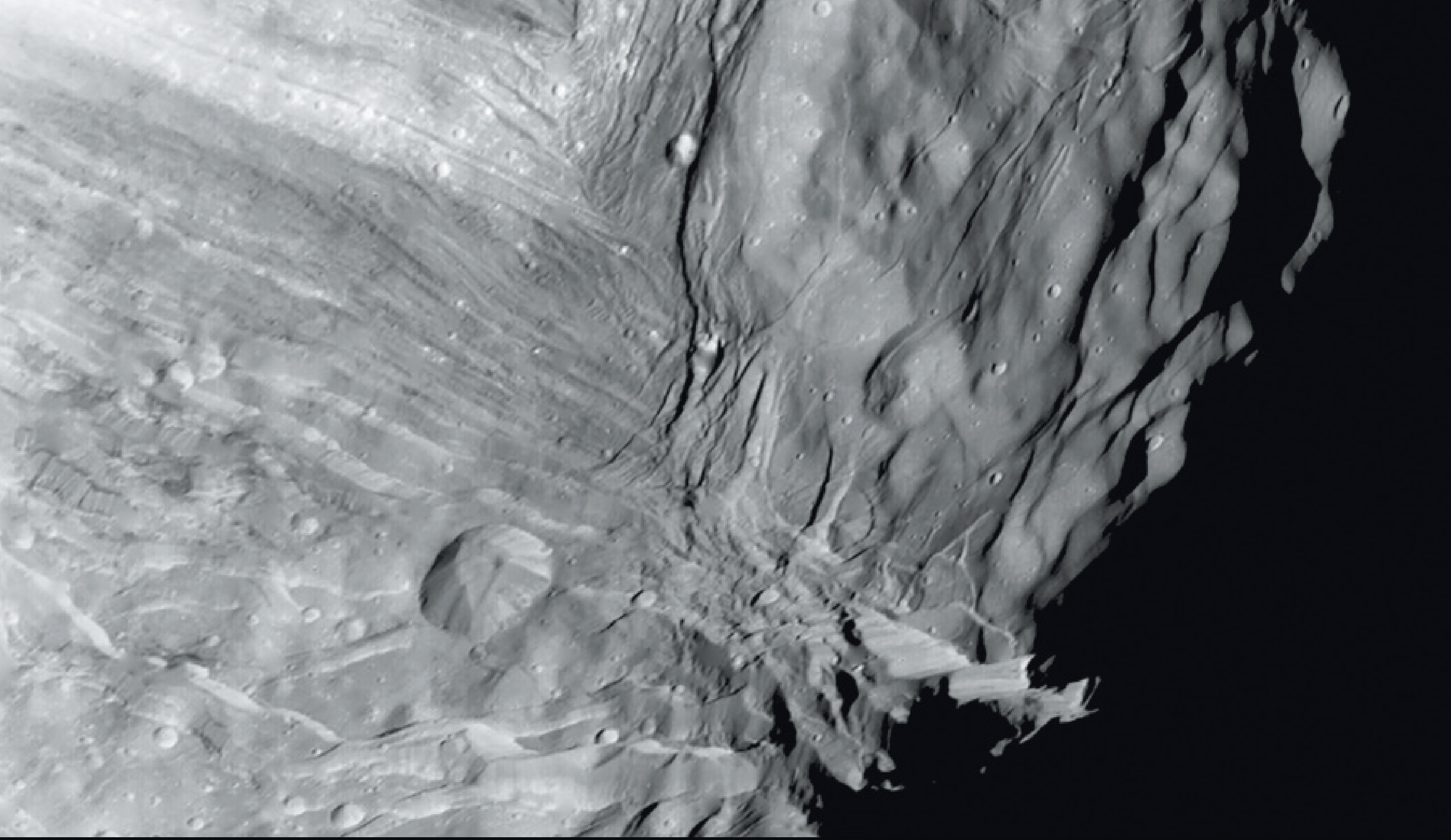
URANUS AND THE EPSILON RING

Digital (non-film) space photography dates back to the use of 1950s-era vidicon cathode ray tube technology that was first developed for television broadcasts. By today's standards, the images taken by such systems are relatively low fidelity, but they were cutting edge for 1970s deep space missions such as the Voyager probes. Voyager 2 used such a vidicon camera to shoot humanity's only up-close photos (so far) of the seventh planet, Uranus, and its faint system of rings. This example (*right*), processed by space-imaging guru Ian Regan, highlights the extremes of performance of early deep space digital cameras. The bright and bluish disk of the planet itself, while bland and cloud-free during the Voyager 2 flyby, reproduced nicely in the camera. But, Regan told me, "I wanted to experiment with the data and produce a composite showing the faint traces of its slender ring system. Enhancement of the vintage TV camera–derived images does indeed reveal the moderately bright Epsilon ring, but also unveils the inevitable carpet of background noise and moiré-like patterns." Such extreme processing might be the only way to pull out subtle discoveries from noisy data, and as Regan noted, might be an inevitable result of "pushing data borne of 1970s technology to its very limit."

New opportunities to view Uranus are in the works: In its decadal survey released in April 2022, the National Academies of Sciences, Engineering, and Medicine recommended the planet as one of NASA's next big targets. In such a mission, an orbiter and atmospheric probe would be launched to Uranus in the early 2030s. With the help of a gravity assist from Jupiter, the spacecraft would arrive at the ice giant 13 years later and start collecting images that Regan and other processors can transform into new art.

Ian Regan





NASA Jet Propulsion Laboratory

VERONA RUPES ON MIRANDA

It has taken 60 years to get to know our planetary neighborhood, photographing and mapping the worlds around us up close for the first time. A notable result, I claim, is that we now know where most of the extraterrestrial natural wonders of our Solar System can be found. These places will be meccas for nature lovers, hikers, and photographers in the centuries ahead. One such place on my personal list is a 20-kilometer-high sheer ice cliff called Verona Rupes (*above*). It was discovered in 1986 on Miranda, a small icy moon of the planet Uranus. This stunning Voyager 2 flyby photo of the cliff is our only good view of it, and it probably doesn't do it justice. Even though Miranda is only about 500 kilometers wide (with the same surface area as Texas), Verona Rupes is the tallest known cliff in the entire Solar System. If (when) you could cliff dive there, it would take more than 12 minutes to get to the bottom because of Miranda's gravity, which is less than one one-hundredth of Earth's. This photo terrifies me because of my fear of heights, but at the same time I am strongly drawn to it because I'm convinced that this place will be treasured in the future by our descendants.

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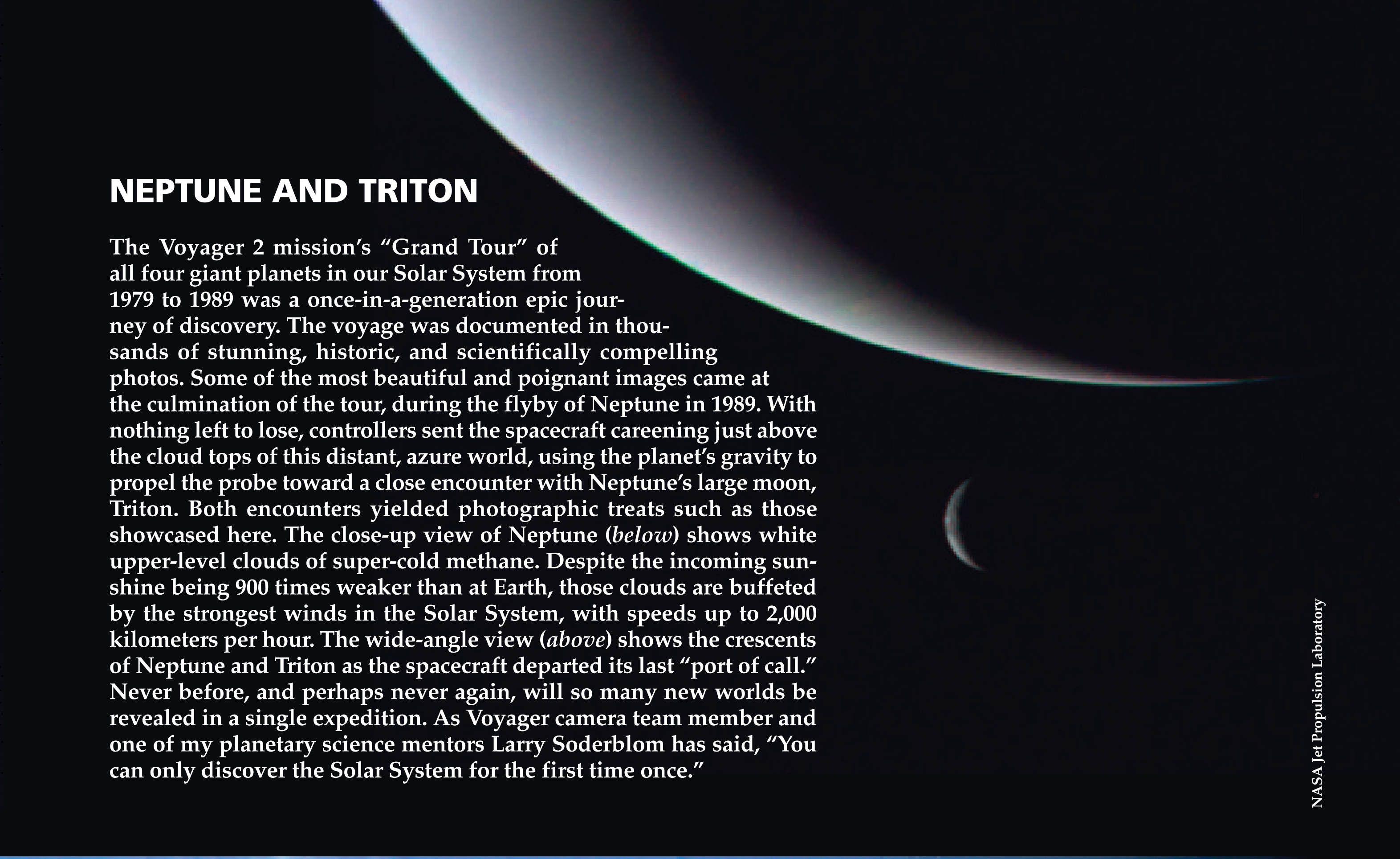
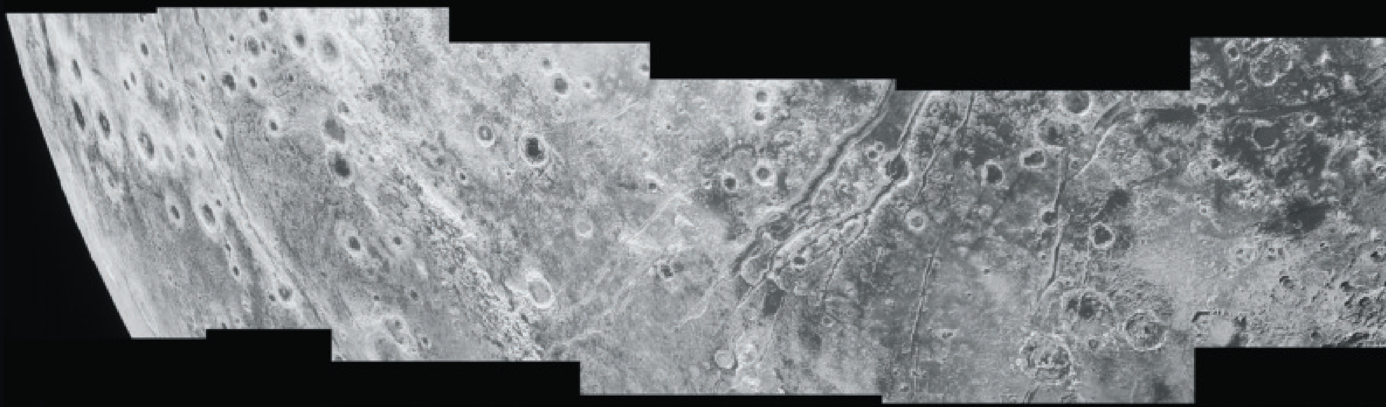


NEPTUNE AND TRITON

The Voyager 2 mission's "Grand Tour" of all four giant planets in our Solar System from 1979 to 1989 was a once-in-a-generation epic journey of discovery. The voyage was documented in thousands of stunning, historic, and scientifically compelling photos. Some of the most beautiful and poignant images came at the culmination of the tour, during the flyby of Neptune in 1989. With nothing left to lose, controllers sent the spacecraft careening just above the cloud tops of this distant, azure world, using the planet's gravity to propel the probe toward a close encounter with Neptune's large moon, Triton. Both encounters yielded photographic treats such as those showcased here. The close-up view of Neptune (*below*) shows white upper-level clouds of super-cold methane. Despite the incoming sunshine being 900 times weaker than at Earth, those clouds are buffeted by the strongest winds in the Solar System, with speeds up to 2,000 kilometers per hour. The wide-angle view (*above*) shows the crescents of Neptune and Triton as the spacecraft departed its last "port of call." Never before, and perhaps never again, will so many new worlds be revealed in a single expedition. As Voyager camera team member and one of my planetary science mentors Larry Soderblom has said, "You can only discover the Solar System for the first time once."

NASA Jet Propulsion Laboratory



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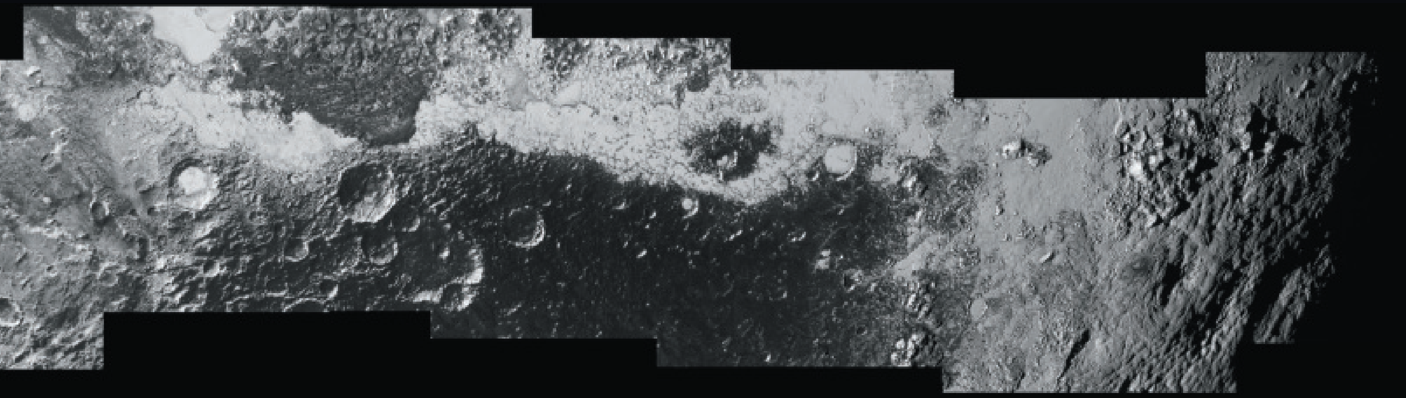
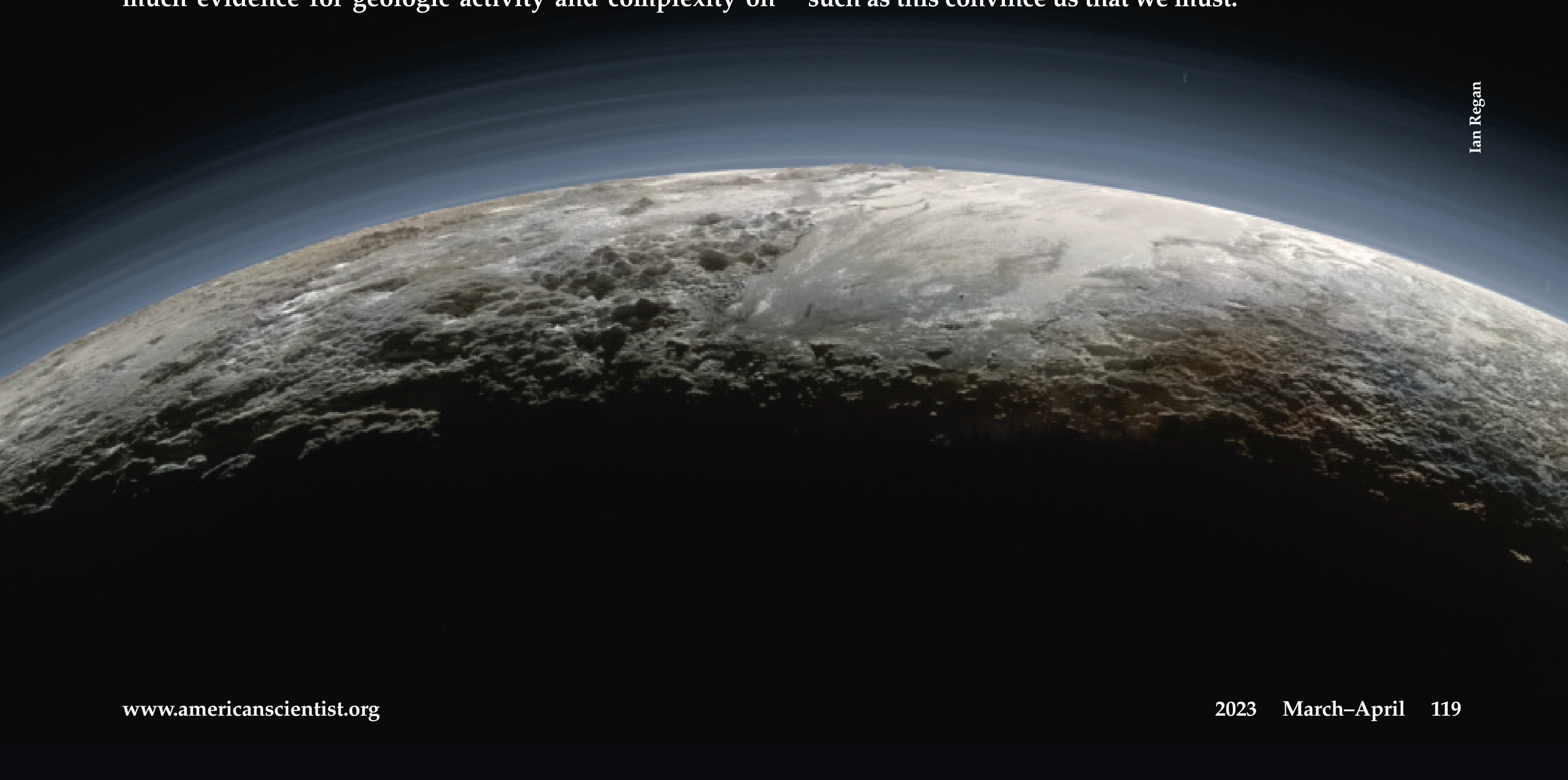


JHUAPL/SwRI

ZIGZAGGING ACROSS PLUTO

Some astronomers classify worlds according to where or what they orbit. But in my experience, most planetary scientists classify worlds according to what they are like. As an example, this gorgeous wide-angle photo (*below*) taken just 15 minutes after closest approach by the NASA New Horizons space probe flyby mission, processed and colorized masterfully by Regan, provides one of the most compelling justifications I know of for classifying Pluto as a planet. Yes, it is a small world in a tilted and eccentric orbit far from the Sun. But it is round from its own gravity. It has an atmosphere, with more than a dozen haze layers highlighted by the backlighting here. Pluto has sprawling icy plains and rugged icy mountains and glaciers, indicating a complex geologic history and an interior likely segregated into core, mantle, and crust. It even has five moons of its own, including one half its size named Charon that is probably also a planet in its own right. "No Earthbound telescope can ever depict distant worlds in such a way, and no other image from this encounter struck such a nerve," Regan told me. He finds the photo profound (and I agree) because "it gave palpable confirmation that, finally, Pluto had become a world reconnoitered by humanity."

Higher-resolution zoomed-in photos of Pluto's surface only enhance the surprise and delight in discovering so much evidence for geologic activity and complexity on such a small and distant planet. The photos above and on the facing page were taken on the same date, but the images have been processed differently. The collage (*above*) shows the planet in light visible to the human eye, whereas the wide-angle image (*facing page*) is a colorized infrared composite that enhances differences in surface composition and physical properties. These images—among the most detailed shot during the NASA New Horizons flyby back in 2015—show a staggering variety of linear faults and circular craters, smooth to rugged textured plains, mountains more than 5 kilometers tall, and strong tonal contrasts among terrains suggesting major variability in ice composition. Where did all the heat and energy come from to drive all this action? This world is 30 to 50 times farther from the heat and light of the Sun than Earth. Tidal forces between this dwarf planet and its five moons are fairly weak. It's made mostly of ice, not rock, and thus lacks the radioactivity that heats rocky planetary interiors. What's going on here in these spectacular and artistically compelling landscape photos from the far reaches of our Solar System is a profound mystery, but one that we need to solve if we're ever going to truly understand planets—of all sizes. No one knows when we'll ever go back there with orbiters, landers, or rovers. But I believe that views such as this convince us that we must.



Ian Regan

The Scientists' Nightstand, American Scientist's *books section, offers reviews, review essays, brief excerpts, and more. For additional books coverage, please see our* Science Culture *blog channel, which explores how science intersects with other areas of knowledge, entertainment, and society.*

ALSO IN THIS ISSUE

THE DEVIL NEVER SLEEPS: Learning to Live in an Age of Disasters. By Juliette Kayyem. page 122

ONLINE

On our *Science Culture* blog: *www.americanscientist.org/blogs/science-culture*

Science Curious Through Science Fiction
The latest episode of *American Scientist*'s science-for-all podcast, DEAI ComSci (Diversity, Equity, Accessibility, and Inclusion), explores how science fiction movies and television shows encourage science curiosity.
www.amsci.org/node/4985

Composite by Robert Frederick

Strangers Among Us

John T. Longino

THE GUESTS OF ANTS: How Myrmecophiles Interact with Their Hosts. Bert Hölldobler and Christina L. Kwapich. xvi + 559 pp. Belknap Press of Harvard University Press, 2022. $69.95.

Studies of ants typically emphasize behavior and the evolution of sociality because they intrigue us as a different kind of society that helps us better understand our own. But there is a second reason to study ants, a second parallel with the human condition, and that involves the intimate associations ants have with many other species.

We increasingly recognize that humans are walking ecosystems, hosting innumerable microorganisms that range from pathogens to beneficial elements of the microbiome. Ant colonies are diverse ecosystems as well. Ant societies attract a remarkable diversity of housemates, known as *myrmecophiles*, that are intimately associated with and dependent on their hosts. These myrmecophiles come from nearly every type of terrestrial life, including microbes, fungi, nematodes, mites, silverfish, crickets, beetles, butterflies, parasitic wasps, and snakes. In some cases, myrmecophiles are beneficial to the ants, but more often they are freeloaders, thieves, murderers, or grifters of all manner.

A book synthesizing the biology of myrmecophiles is long overdue, and now we have it. In *The Guests of Ants*, Bert Hölldobler and Christina Kwapich introduce us to this amazing menagerie, synthesize centuries of observations, and bring us up to speed on the latest science. The book is technical and densely packed with information, clocking in at 559 pages, and has the potential to be a long-lasting benchmark and resource for the specialist. But it is also a pleasure for any curious naturalist, flipping through the pages to land on images of remarkable creatures with remarkable stories. On one page, a new leafcutter ant queen, about to take flight, has two miniature cockroaches perched on her back; we learn that these tiny roaches, *Attaphila fungicola*, are myrmecophiles that hop a flight with a new queen to disperse to new colonies. On another page, workers of the ferocious weaver ant (*Oecophylla*) investigate what looks like a nicely browned loaf of bread in their nest, but which is, in fact, the pupa of a butterfly (*Liphyra*), whose larvae grow up feasting on ant larvae and whose skin has special structural modifications that protect it from ant bites.

The epilogue is worth reading first. In addition to concluding statements, it also explains why such a diversity of organisms has specialized in living with ants. First, the ant nest represents "an ecological island lavishly endowed with nutrients," and is thus a target for colonization. Second, ant colonies are "porous to invasion" because ants are social. Ants have evolved in various ways to recognize nestmates, often using a kind of chemical code. As with human interactions, these secret codes are vulnerable to being cracked by outsiders, and myrmecophiles have insinuated themselves into ant life by mimicking the diverse forms of communication that ants use.

The first chapter of the book is a primer of ant biology, followed by nine chapters about particular groups of myrmecophiles or common adaptations. Each of the chapters could be a stand-alone review, but together they provide a complete picture of the ant ecosystem. One chapter covers the lycaenid butterflies that have close asso-

Courtesy of Alex Wild/alexanderwild.com

***Attaphila fungicola*, which can be seen in the top picture, is a myrmecophilus cockroach. As seen in the second picture, it attaches itself to alate queen ants, who will eventually start their own nests. The attaphila travel to new colonies by hitching a ride on the queen ants when they go on mating flights.**

ciations with ants, either as mutualists or predators. Another chapter is all about mimicry of ant workers, especially by spiders.

Two generations of Hölldoblers have been studying myrmecophiles. The work of both Bert Hölldobler and his father Karl is thoroughly reviewed, revealing the elaborate behavioral and morphological specializations of myrmecophilous beetles. The biology of the aptly named ant-loving cricket gets its own chapter, highlighting Kwapich's work on the mystery of size-matching between these cricket guests and their ant hosts. The final chapter summarizes vertebrate associates of ants, from blind snakes to the anting behavior of some birds. There is a glossary and a full 44 pages of references, and the entire book is copiously illustrated with photos or artful depictions of ants and their associates.

The natural history of myrmecophiles is a knowledge base that builds upon itself. Erich Wasmann was a late 19th-century and early 20th-century entomologist who used studies of myrmecophiles to inform debates on evolution and the role of natural selection. Although his evolutionary theorizing is rarely cited today, he also made careful and detailed observations of the natural history of myrmecophiles. It is satisfying to see Wasmann references from the 1890s in this book, cited not as historical footnotes, but as sources of knowledge no less relevant than a 2022 reference. I also appreciated the attention paid to taxonomic changes. Many studies of myrmecophile biology were developed using a taxonomy that was static for decades or centuries. It was a taxonomy that had no problem putting highly derived specialists such as significantly modified myrmecophiles in separate genera or families at equal rank to their unspecialized relatives, from which they arose. The phylogenetics revolution that began in the 1950s and continues to the present day has resulted in an extended period of nomenclatural instability, due to both revised ideas of phylogeny and a desire for nomenclature to reflect phylogeny. Hölldobler and Kwapich take pains to explain very recent nomenclatural changes to taxa with long histories of investigation under older names.

In addition to being a broad survey of descriptive natural history, there is also a strong hypothesis-testing framework in the book. Often studies are summarized, and then critically evaluated. Instead of just "This study did *X* and found *A* and *B*," it is often "This study did *X* and found *A* and *B*, but support for *B* is not strong, and *C* is also a possibility, and it would be interesting to do *Y* to test whether *B* or *C* is more likely." Thus, the book is not merely a dry compendium of facts, but rather, it is full of opportunities for critical thinking.

E. O. Wilson famously quipped that ants are "the little things that run the world." *The Guests of Ants* reveals that they not only run the world, they *are* the world for thousands of other species that have evolved to depend on them. Although biodiversity conservation is not emphasized in the book, the implications are clear: Conserving ant diversity protects far more than the ants themselves.

John T. Longino is a professor at the University of Utah School of Biological Sciences. His research is a mix of ant taxonomy and phylogenetic systematics, as well as macroecological studies of ant diversity on elevational gradients. Most of his field research has been carried out in the Neotropics, especially the middle American corridor.

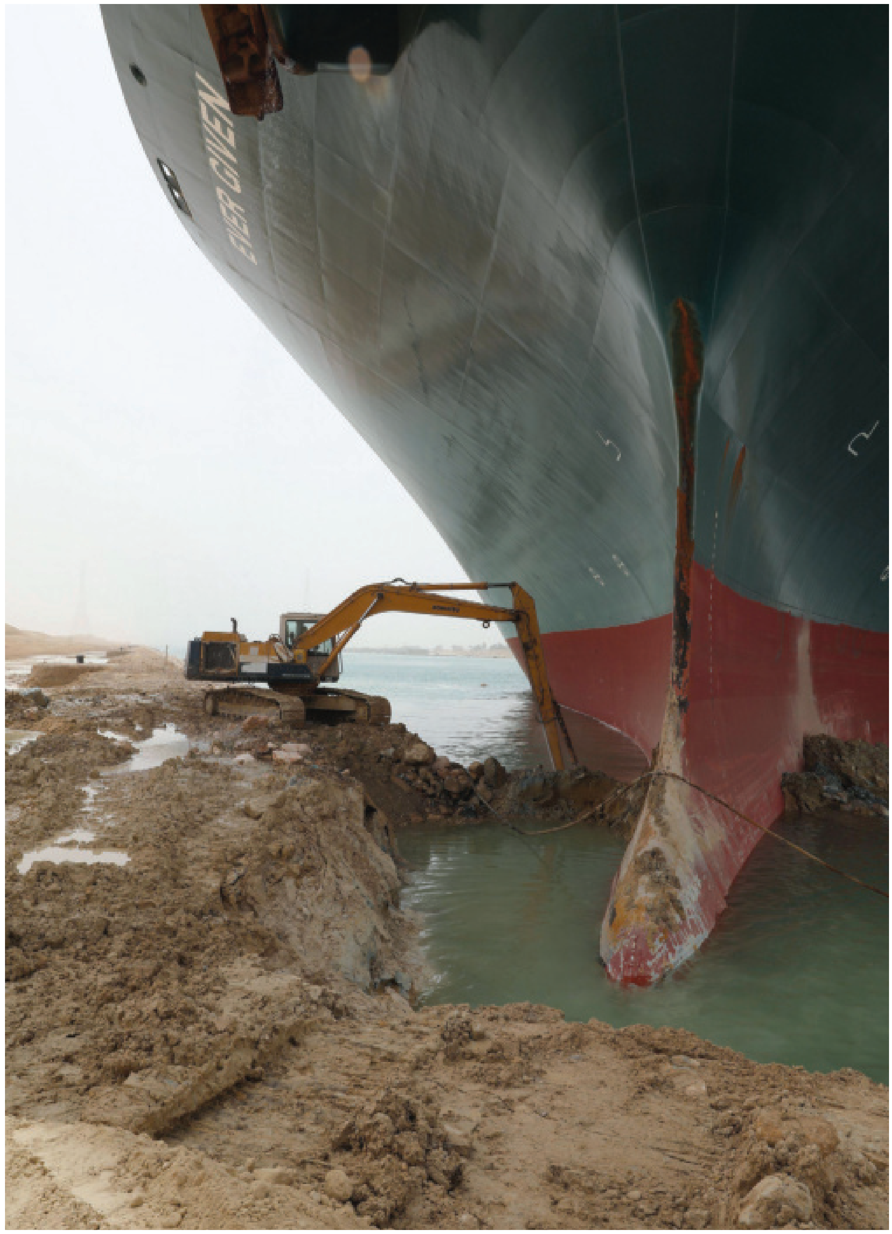
Living in an Age of Extremes

Lori Peek

THE DEVIL NEVER SLEEPS: Learning to Live in an Age of Disasters. Juliette Kayyem. 240 pp. PublicAffairs, 2022. $17.99.

I was first introduced to the study of disasters in 1999, when I joined the Natural Hazards Center at the University of Colorado, Boulder, as a graduate assistant. Back then, researchers would often refer to these calamitous incidents as "low-probability, high-consequence events." Even for a newcomer to the field, the message was clear: Disasters don't happen all that often, but when they do, they cause widespread damage and suffering.

In *The Devil Never Sleeps*, Juliette Kayyem takes that old saying, and the ideas underlying it, to task. She writes in the opening pages that "Disasters and crises are not . . . rare occurrences; they are standard operating procedure. . . . Once we can all accept this lived reality—that the devil never sleeps—then we can better prepare for when the next one comes because it will come, as will all the ones after that." Her words reflect dire statistical trends such as those showing that, on average, a disaster happens every day somewhere in the world. The book also captures a more general shift in the study of disasters, in that they are no longer being treated as infrequent events that only temporarily disrupt the social order, but as commonplace events.



UPI / Alamy Stock Photo

One of the many failed attempts to get the *Ever Given* unstuck from the Suez Canal. Source: Suez Canal Authority.

The rising number of disasters globally is being driven by a complicated web of forces related to global warming, infrastructure decay, unsustainable development in hazardous areas, population growth, technological change, and rising economic and social inequality. The book's central thesis is that the sooner we accept the reality that we live in an era of recurrent disasters, the sooner we can ready ourselves to respond in a way that will make even the worst incidents somewhat less bad. Kayyem calls this *consequence minimization*, and she draws on her decades of crisis management experience to offer lessons on how to turn high-probability disasters into low-consequence events.

For Kayyem, disaster comes in an almost dizzying array of forms—from climate catastrophe and global pandemic to hurricanes, tornadoes, tsunamis, wildfires, school shootings, terrorist bombings, oil spills, cyberattacks, and power grid failures. She refers to these widely varying events—whether it be the 2010 Haiti earthquake that killed hundreds of thousands of people or Jet Blue airlines doing a poor job of deplaning hundreds of anxious passengers during an ice storm—as the moment of the "boom." Also in her framework, there are two moments; the before ("left of boom") and after ("right of boom").

In the United States and most other nations around the world, far more funding is committed to "right of boom" disaster response and recovery activities, rather than to "left of boom" prevention efforts meant to stop the disaster from occurring in the first place. To put it another way, government agencies dump much more money into fighting fires than into ensuring the conflagration never begins. Charitable giving operates in much the same way on a global scale, with an estimated 90 percent of disaster-

related donations going toward emergency relief efforts.

Kayyem takes this lack of investment in disaster risk reduction as a given, and she does not dwell on how little is done to mitigate harm. Instead, her stated focus is on describing how we can brace for the many different disruptions that occur *after* disaster has already struck. The challenge with this emphasis, however, is that societal investments "before the boom" matter most in reducing the worst consequences. For example, if you live in earthquake country and want to save lives, perhaps the most important things you can do are to retrofit existing buildings and construct new seismically sound structures that will not collapse when the earth shakes. This is not to suggest that dedicating resources to rescue and response efforts is not important, but rather to underscore how crucial it is to focus on mitigation investments in order to truly minimize consequences. It would have dramatically strengthened the book if Kayyem had made this point about the linkages between the before and after times much more explicit.

To put it another way, government agencies dump much more money into fighting fires than into ensuring the conflagration never begins.

The Devil Never Sleeps is organized around eight foundational lessons of disaster management that Kayyem argues can and should be implemented now, to help people ready themselves for this age of extremes. She frames each key principle in a straightforward way and buttresses her arguments with plenty of memorable examples. She writes clearly and retains a sense of humor, even as she addresses deadly serious topics.

Following the introduction, the first three chapters focus on cultivating a disaster management mindset ("assume the boom") and on the basics of communication and emergency response. Kayyem makes an especially effective case regarding the need for unity of effort during a crisis. As she notes, these activities may be spontaneous, as when volunteers converge at the scene of a disaster, or they may be cultivated within and across governance structures to ensure that institutions can withstand a disaster, such as when the new leader of the Transportation Security Administration subjected the agency to a complete overhaul to encourage counterterrorism efforts and customer engagement.

The next three chapters are about how corporate leaders and government officials can institute best practices to limit harm once disaster inevitably strikes. Case studies drive home why relying on a singular "last line of defense" to avert disaster does not work. Here, Kayyem vividly describes failures, such as the reliance on a sole blowout preventer on the *Deepwater Horizon* oil rig, and how the use of a lone evacuation route left residents vulnerable to injury and death in the catastrophic wildfire that swept through Paradise, California, in 2018. Because disasters often co-occur, this section of the book also highlights the need to minimize cascading losses in compound events. For example, during Hurricane Maria, a few dozen people likely died due to the direct effects of the storm's lashing winds and torrential rains. Thousands more people—including a disproportionate number of older adults, people with chronic health conditions, people living in poverty, and people living in rural areas—lost their lives due to weeks-long power outages, road closures, and other response failures.

The closing chapters include what might best be characterized as disaster success stories and offer suggestions for how professional disaster managers can learn from the last big event and prepare for the next one. For example, Kayyem recounts how the

When people can barely make their monthly rent, it seems a little precious to discuss building bandwidth.

owners of the restaurant chain Chipotle effectively responded to what could have been a devastating *E. coli* outbreak by closing stores, working closely with the Centers for Disease Control and Prevention, and communicating honestly about what happened. This and other examples in the final chapters demonstrate that consequence minimization is possible when decision-makers take the time to learn from past events and utilize those lessons in planning activities meant to reduce future harm.

The Devil Never Sleeps sets out to do two things: To convince the reader that disasters are now part of our normal, (un)steady state, and to make the fundamental lessons of disaster management accessible to everyone because "we must all consider ourselves disaster managers." Kayyem succeeds wildly in showing how disasters can and do take many forms and can come at any time. But the book falls short in explaining how we all can truly adopt the recommended steps in the book.

Although Kayyem states that the book is for everyone, many of the actions described require power, access to resources, and decision-making authority. Kayyem acknowledges in the closing chapter that she is "well aware that the ability to prepare for disaster management is often the luxury of those with time and capacity. When people can barely make their monthly rent, it seems a little precious to discuss building bandwidth." She does not, however, dedicate space in the book to exploring how the millions of people in the United States, as well as the billions globally, who are living in economically precarious situations can become "disaster managers." This is a major omission precisely because people living in poverty, as well as other socially marginalized groups, are the ones who are most likely to suffer disproportionately when disaster strikes. Given the significant problems of structural racism and historic gaps between the rich and the poor, this is a significant oversight. Moreover, because so many of the risk-generating activities that occur in society—such as corporations that spew pollutants into the air and developers who build shoddy housing in floodplains—occur outside of the purview of average citizens, it feels all the more pressing to address who is actually responsible for managing the disasters that Kayyem so unforgettably describes.

The Devil Never Sleeps certainly opens up an important conversation regarding the impossibility of eliminating all risks in this era of recurrent disasters. It also highlights important steps that can and should be taken by professionals to minimize the worst consequences. Because Kayyem does not consider which people are most subject to disaster, this is a conversation that still needs to continue, given exactly how much is at stake.

Lori Peek is professor of sociology and director of the Natural Hazards Center at the University of Colorado, Boulder. An expert on marginalized populations in disaster, she is author of the award-winning book Behind the Backlash *(Temple University Press, 2011) and co-author of* The Continuing Storm *(University of Texas Press, 2022).*

Volume 32 Number 02

Sigma Xi Today

A NEWSLETTER OF SIGMA XI, THE SCIENTIFIC RESEARCH HONOR SOCIETY

Sigma Xi Launches New Volunteer Portal

Sigma Xi recently announced the debut of a new online platform that provides opportunities for members and volunteers to connect and engage in Society programs, mentorship opportunities, and chapter events. The new volunteer portal was built through a partnership with Galaxy Digital, an Asheville, North Carolina–based software company that helps nonprofits track and manage volunteer opportunities and community impact.

The new portal is free to use for members and nonmembers. Individuals can create user accounts to gain easy access to opportunities at both the local and national levels. Volunteers can use the portal to track their hours and receive prizes and awards for their service.

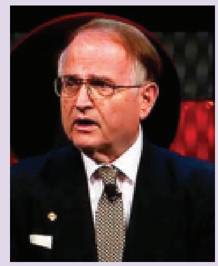
Available opportunities include mentoring, evaluating abstracts, and judging for programs such as Sigma Xi's Grants in Aid of Research and IFoRE student research presentations. Additionally, members will be able to find and showcase events for chapters and regional constituencies, including members-at-large. In addition to providing a single location where people can track upcoming events and program opportunities, the portal serves Sigma Xi's ongoing mission to foster new generational growth in the research enterprise through mentoring and student–professional networking opportunities.

To get started on the platform, members and interested individuals should visit **sigmaxi.galaxydigital.com**.

Sigma Xi Today is managed by **Jason Papagan** and designed by **Chao Hui Tu**.

From the President

Two Pillars of Modern Science: Translation and Communication



Since the conclusion of our recent IFoRE conference, I have been thinking about the future of science and the way we do research. Many of us once pursued purely fundamental research. Why? Well, first, it was satisfying. It was always being built upon the edifice we had already started building. I am an engineer by training, and I believe many engineers are (or were) crypto-scientists. The funding system and the way we were doing things in the 1970s and 1980s were very favorable for many of us. I distinctly recall a senior colleague at Purdue University, where I worked at that time, looking at my CV and commenting, "What is this paper in the *Journal of Applied Polymer Science*? What does 'applied' mean? Science is science."

He may have had a point: Fundamental research simply had to be done. Let's not forget just how many fundamental leaps later led to major advances in computers, microelectronics, sensors, nanomaterials, and so much more. But things changed drastically by the mid-1980s. The days of limitless funding for academic projects had passed. By the early 1990s, it became clear that what academics like me were doing had to have more applicable or applied aspects. Questions first came from the public—and one or two maverick senators (at least in the United States)—asking what the purpose of research even was. Affected by this new way of thinking, scientists began to realize that working on fundamental problems because "we like to work on them" was not enough, and was no longer appropriate in the modern cultural milieu. I recall my first talk at a European university in 1992, where I uttered the opinion that European taxpayers should not be supporting professorial salaries for the purpose of the proliferation of awards, or because professors should be allowed to continue doing what "they like best."

Now research has taken on yet another new face. It must be translational in the broad sense of the word, in that it must be applied and communicated to all fields. Many scientists still do not realize that we are responsible first and foremost for effective communication. Many continue to believe that ignorance about science simply amounts to a lack of information, and that if people are simply given facts, they will become science supporters. Yet the best means of effective science communication include cultural sensitivity, finding common ground, employing accurate narratives, and connecting with people. Thus, there is an obvious need to bring together researchers and science communicators for closer collaboration.

As evidenced by the recent COVID-19 pandemic, scientific misinformation can spread quickly, causing serious damage to society. Effective, accurate science communication skills can have a broad, positive impact on society, as well as the culture and norms of scientific academia itself.

Nicholas A. Peppas, ScD

2022 Sigma Xi Election Results

Members of Sigma Xi, The Scientific Research Honor Society elected their peers to leadership roles in an online election held November 7–20, 2022. Sigma Xi thanks all members who voted or volunteered to run as candidates.

Kathy Lu won the presidential election. On July 1, 2023, she will begin a three-year term that will consist of one year each as president-elect, president, and immediate past-president. Dr. Lu is a professor in the Materials Science and Engineering Department at Virginia Tech University. She also currently serves as the Director of the Artificial Intelligence–Guided Materials Thrust in the College of Engineering, and Director of Graduate Assistance in the Areas of National Need Program. Her primary research interests are materials synthesis; processing, characterization, and fundamental studies; energy materials; and harsh environment materials.

All newly elected leaders are listed below with their Sigma Xi chapter affiliations. President, treasurer, directors, and associate directors will serve three-year terms beginning July 1, 2023. Committee on Nominations representatives began three-year terms immediately following the election.

President-elect
Kathy Lu
Virginia Tech University

Director: Members-at-Large
Emma Perry
Members-at-Large

Director: Mid-Atlantic Region
Deborah Good
Virginia Tech University

Director: Northeast Region
Theodora Pinou
Western Connecticut State University

Director: Research and Doctoral Universities Constituency Group
Ray Byrne
University of New Mexico

Associate Director: Area Groups
Elizabeth Ambos
District of Columbia

Associate Director: Comprehensive Colleges Constituency Group
He Wang
Queens College

Associate Director: Northwest Region
Allen Thomas
University of Nebraska at Kearney

Associate Director: Southeast Region
Lei Sun
Georgia Institute of Technology

Committee on Nominations: Canadian/International
Richard Boudreault
Sigma Xi McGill

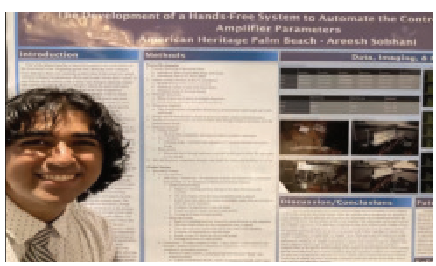
Committee on Nominations: North Central Region
Carlo Segre
Illinois Institute of Technology

Committee on Nominations: Southwest Region
Bob Horton
Rice University–Texas Medical Center

To nominate candidates for the 2023 elections, please visit **sigmaxi.org/elections23.**

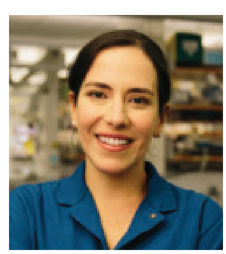
Post-Conference Award Winners

Immediately following November's inaugural International Forum on Research Excellence (IFoRE), a special virtual event was held to present two post-conference awards. The event was hosted by Sigma Xi's president-elect, Marija Strojnik, who presented American Heritage Palm Beach High School student Areesh Sobhani with the inaugural IFoRE President-elect Award for his research presentation on the development of a hands-free system to automate the control of guitar amplifier parameters. The virtual ceremony also featured a presentation from 2022 Bugliarello Prize winners Markita Del Carpio Landry and Madeline Klinger. The University of California, Berkeley researchers were recognized for their *American Scientist* article "Tiny Lights in the Brain's Black Box," which explores imaging brain chemistry in real time using fluorescing carbon nanotubes switched on and off with synthetic DNA.



Areesh Sobhani

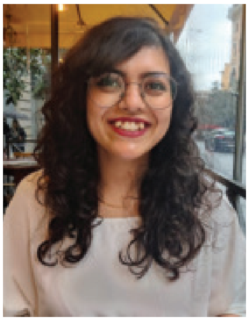
Madeline Klinger



Markita Del Carpio Landry

FACES of GIAR : Soumya Varma

Grant: $1,000 in Spring 2021
Education level at time of the grant: PhD student



Project Description: The principal objective of the research was to understand the structure-property relationship of the enamel known as crenulated wavy enamel (CWE) in the grinding dentition of large herbivore hadrosaurid dinosaurs. The grant was used to buy an instrument attachment, namely a diamond indenter tip, to evaluate wavy enamel's micromechanical response. The indenter tip was attached to the HysitronTI950 nanoindenter, and nanoindentation experiments were carried out to evaluate its mechanical properties at a small scale.

How did the grant process or the project itself influence you as a scientist/researcher? The writing of the grant proposal enriched my experience in writing. It made me understand the key points required to write a successful proposal. The most helpful aspect was learning how to write about my research concisely and for a broader audience. The budgeting process also taught me how to identify what to include and what to leave out. The grant also helped me get another scholarship, which funded a future visit to Switzerland.

What is one piece of advice or tip you would give to future grant applicants? Focus on creating a very strong background section, target a broad audience, and include a comprehensive budgeting section.

Sigma Xi Chapter of Excellence Awards

The 2022 Sigma Xi Chapter Award winners were presented at the Society's annual Assembly of Delegates. The festivities kicked off the inaugural International Forum on Research Excellence (IFoRE) in Alexandria, Virginia. Finalists were chosen by regional and constituency directors based on information in the chapters' annual reports, and winners were selected by the Committee on Qualifications and Membership.

The Assembly of Delegates is an annual gathering of chapter representatives worldwide to act on business and governance items, as authorized by the Society's bylaws and constitution. Delegates vote on governance decisions and resolutions that guide Sigma Xi's mission and vision, including decisions related to programs, chapters, membership, and IFoRE. After conducting the business of the Society, delegates participate in IFoRE in a variety of ways, including as organizers, speakers, presenters, judges, award recipients, mentors, and artists.

Chapter of Excellence Awards
Bestowed on chapters for exceptional chapter activity, innovative programming, and true community leadership

Winners
Barry University
East Stroudsburg University of Pennsylvania
National Institute of Standards and Technology
Quinnipiac University
University of Cincinnati

Honorable Mentions:
Northwestern Pennsylvania
University of Michigan

Chapter Program of Excellence Awards
Bestowed on chapters that organized or hosted a single outstanding program

Triple Cities New York for "The Southern Tier Scholastic Science (Fair) TikTok Challenge"

Woods Hole for "Undergraduate Ethics Program"

Northwestern Pennsylvania for "Student Research Conference"

Top Electing Chapters
Bestowed on chapters that had the most newly elected members

Area Groups, Industries, State, and Federal Laboratories Constituency Group
Southern Maine

Baccalaureate Colleges Constituency Group
Carleton College

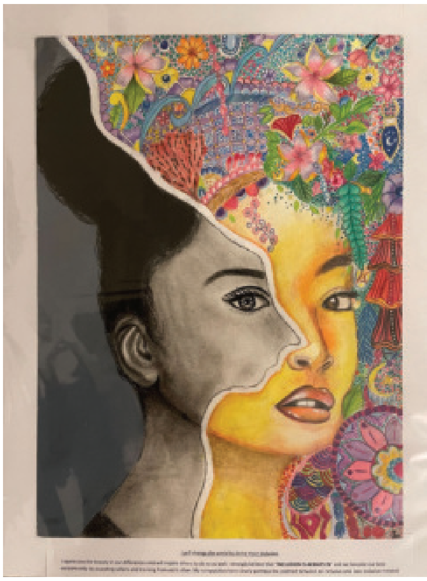
Canadian/International Constituency Group
Calgary

Comprehensive Colleges and Universities Constituency Group
Fairfield University

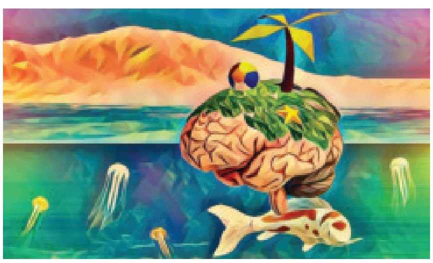
Research and Doctoral Universities Constituency Group
Brown University

Top Electing Member-at-Large (Top Nominating Individual)
Michael Cloud

STEM Art and Film Festival Awards



Inclusion and Human Psychology



A Brain Vacay for You: Swimming in Serenity

Sigma Xi is proud to announce the winners of the 2022 STEM Art and Film Festival. Held virtually on November 6, the festival celebrated the intersection of science and art through visual and performing art that reflected or was inspired by science, technology, engineering, and math. Artists submitted and showcased their work in a virtual exhibit hall and entries consisted of visual art, digital art, films, documentaries, animations, and performance art. Sigma Xi congratulates all the 2022 winners and honorable mentions below.

Best Overall Artwork
Inclusion and Human Psychology
Khushi Garg

People's Choice Award—Artwork
A Brain Vacay for You: Swimming in Serenity
JH Miao

Best Film
Can Archaeology Repair Its Past with Indigenous America?
Victoria Sutton

People's Choice Award—Film
Ligo
Les Guthman

Best Short Film
But What Is CRISPR-CAS9? An Animated Introduction to Gene Editing
Harrison Ngue

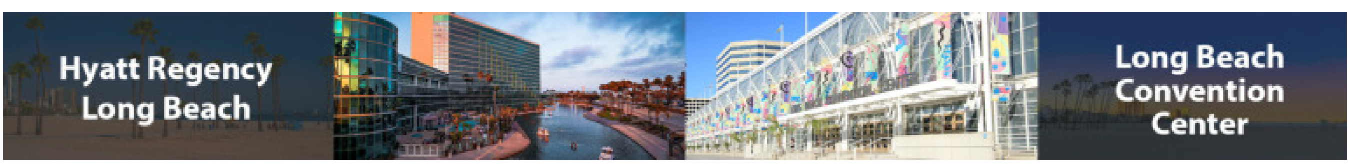
Best Performing Arts
Asymptote
Stephanie Chou

Honorable Mention—Film
Student-Made Interactive Learning with Educational Songs (in Introductory Statistics)
Lawrence Lesser

Honorable Mention—Performing Arts
Music of the Spheres
Lawrence Lesser

Honorable Mention—Artwork
A Visualization of Algorithmically Generated Artwork
Michael Wehar, Alyssa Zhang, Maya Newman-Toker, and John Mancini

Save the Date for IFoRE '23 in Long Beach, California



Mark your calendars for November 10–12, 2023, as Sigma Xi's International Forum on Research Excellence (IFoRE) lands in Long Beach, California. With the theme of "Vision for Ethical Research," Sigma Xi invites all scientists, engineers, ethicists, students, and science communicators to attend or present sessions at the 2nd annual conference. Abstract submissions will be accepted for Key Thought and breakout sessions, including symposia, workshops, panel discussions, and research and individual presentations. A preconference Assembly of Delegates for Sigma Xi chapter leaders and constituency representatives will take place on November 9 at the Long Beach Convention Center. For more information on upcoming registration and proposal submissions, visit **experienceIFoRE.org**.

IFoRE

POWERED BY SIGMA XI

International Forum on
Research Excellence

SAVE THE DATE

November 10–12, 2023

Meeting of Delegates
November 9

Long Beach, California